ACCUMULATION OF SEDIMENT AND RADIONUCLIDES IN TIDAL MARSHES OF THE MURDERKILL RIVER ESTUARY, DELAWARE

by

Dack Giles Stuart

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 Approved:
 Christopher K. Sommerfield, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

 Approved:
 Charles E. Epifanio, Ph.D.
Director of the School of Marine Science and Policy

Approved:

Nancy M. Targett, Ph.D. Dean of the College of Earth, Ocean, and Environment

Approved:

Charles G. Riordan, Ph.D. Vice Provost for Graduate and Professional Education

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ABSTRACT

This thesis examines patterns and rates of sediment accumulation and tidal marsh accretion in the Murderkill River estuary, Delaware, with special emphasis placed on changes in accumulation rates and sediment physical properties associated with historical land-use practices, such as mosquito ditching. Over 90% of United States Atlantic East coast salt marshes have been ditched to some degree, but little quantitative work has been done to examine the specific effects on marsh sedimentary processes. An understanding how these ditches have affected sediment delivery to and retention on the marsh platform will provide insight into how ditched marshes are likely to respond to changes in sea level, sediment availability and vegetative growth.

To investigate historical changes in sediment composition of the marsh sediment column, the specific contributions of mineral and organic solids and water/entrapped gas were determined from measurements of sediment dry-bulk density and loss-on-ignition. Additionally, grain-size analysis was conducted to determine the textural composition of sedimentary particles delivered to the marsh. Downcore profiles of the radionuclides ²¹⁰Pb and ¹³⁷Cs were used to determine sediment accumulation and marsh accretion rates, to develop chronologies for the sediment column, and also as indicators of sediment transport pathways within the marsh. In addition, an historical investigation was conducted to learn more about past land-use practices and sources of human disturbance in the estuarine system.

Spatial and temporal variations in the relative contributions of organic and mineral matter to total sediment volume show that marsh accumulation in the Murderkill is dominated by mineral matter and that the organic contribution has varied

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little over the past century. At two upriver sites, changes in dry-bulk density, loss-onignition and grain size were observed and interpreted to correspond to the transition from freshwater marsh to brackish marsh. Although the cause of this change is unknown, it cannot be directly associated with mosquito ditching in the lower estuary due to the distance separating these sites from ditched areas. Vertical accretion rates (0.3–0.7 cm/yr) determined for undisturbed marsh sites are comparable to rates computed for other salt marshes of the greater Delaware Estuary. Radionuclide focusing factors for the marsh sites indicate that the Murderkill is a well-mixed estuary, consistent with results from a previous study of hydrodynamics of the Murderkill River.

Temporal changes in accumulation (organic vs. mineral) were observed at one inter-ditch site, but the change cannot be directly associated with ditching activities because similar trends are not evident in other inter-ditch cores. Ditches filled rapidly with mineral mud after being excavated but have not matched the adjacent marsh elevation, possibly because they are acting as the preferred tidal pathways into and out of the marsh. Ditches have not significantly affected the median grain size and sorting of inter-ditch or ditch sites compared to a similarly located non-ditched location. There is no evidence to suggest ditches have deprived the marsh platform of suspended sediment in order to infill. The sedimentary record suggests that the effects of ditching on the adjacent marsh platform are subtle and not always similar among depositional sites. Thus, the results of this study suggest that there is no specific sedimentary response to ditching in ditched or non-ditched areas of the same marsh.

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Chapter 1

INTRODUCTION

1.1 Salt Marsh Sedimentation

Much of the coastline along the United States Atlantic coast is characterized by salt marshes (Reed et al., 2008). Historically, marshes have long been regarded as inhospitable threats to public health, harboring flies and mosquitoes responsible for spreading diseases like malaria and West Nile virus. Until the midtwentieth century, marshes were used as dumping grounds and consequently polluted with industrial runoff (Gedan at al., 2009). In reality, salt marshes are vital sources of food, shelter, and nurseries for a variety of marine, terrestrial and migratory species (Boesch and Turner, 1984; Burger et al., 1997; Silliman and Bertness, 2002; Gedan et al., 2009). They also serve as a buffer zone between the terrestrial and marine ecosystems where sediment, nutrients, organic carbon and pollutants from land are retained (Kennish, 2001; Gedan et al., 2009). Marshes are also used for commercial purposes and recreation (Kennish, 2001). Scientific and conservation efforts have been established to better understand and protect these fragile ecosystems and in recent years understanding how marshes maintain their elevation with respect to rising sea level has become an area of vigorous research.

Accumulation of mineral and organic mass leads to vertical *accretion* of the marsh on the long term. Two of the most important processes affecting marsh accretion and elevation change are allochthonous mineral sediment accumulation on the marsh surface and autochthonous vegetative growth. A conceptual model of

sediment accumulation in salt marshes is shown in Figure 1. Inorganic (mineral) sediment is perhaps the overarching factor influencing marsh elevation because it is the substrate upon which the entire marsh accretes. It is well-known that mineral sediment directly adds to the vertical accretion of a marsh and that it is a source of nutrients for vegetation (DeLaune et al., 1983). The processes controlling mineral sediment production can involve erosion in uplands or mobilization from aquatic sources followed by transport to the marsh through the watershed directly or through tidal currents as suspended sediment. Mineral sediment can also be redistributed within a system once it has been deposited within the estuary. Sediment transport and deposition are extremely complex processes and are influenced by a multitude of environmental properties (French, 2006). Average grain size and current velocity determine if the water is moving fast enough to entrain and mobilize sediment (Dyer, 1986). Biogenic compounds, such as those found in biofilms, influence erosion capabilities of sediment as well (de Brouwer et al., 2000).

Vegetation on the marsh surface adds to marsh elevation is several ways. First, vegetation canopy reduces the flow speed of water during over-marsh tides and enhance settling and accumulation of suspended sediment on the marsh surface (Stumpf, 1983; Friedrichs and Perry, 2001; Morris et al., 2002). Increased stem density also reduces ebb tide velocity at the marsh surface, reducing the likelihood of sediment being eroded (Gleason et al., 1979; Leonard and Luther, 1995). Additionally, sediment can adhere to plant stems and leaves and can be washed off by rain and tides (Stumpf, 1983). Lastly, vegetation in the form of above-ground (plant stems), below-ground biomass (roots) and deposition of detrital plant fragments contribute to accretion on the marsh surface (Stumpf, 1983). Subsurface decay of

organic material counters burial of new organic material and contributes to reductions in marsh elevation. If surface root material is lost, the marsh's ability to maintain pore space and hold water volume is also greatly reduced (Turner et al., 2000).

Tidal influences on marsh elevation are numerous. Tidal hydroperiod the duration and frequency of tidal flooding — is the most important aspect affecting sediment availability, (Friedrichs and Perry, 2001). Hydroperiod is affected by the elevation of the marsh platform within the tidal frame: lower areas will be flooded more frequently and for longer time intervals while higher areas will flood less frequently and for shorter periods. Increasing flood duration grants more time for suspended sediment to become deposited on the marsh surface. In this way lower areas will experience larger accretion rates, thus increasing the local elevation and bringing these areas closer to the elevation of higher areas (Temmerman et al., 2005). Accretion has a well-documented relationship between hydroperiod concluding that areas with longer hydroperiods should accrete more sediment (Cahoon and Reed, 1995; Temmerman et al., 2005; French, 2006). Salt marshes must accrete vertically at rates equal to or greater than the local rate of sea level rise otherwise the marsh will become permanently flooded, vegetation will drown and the marsh will potentially be converted to open water (DeLaune et al., 1983; Orson et al., 1985; Allen, 2000; Friedrichs and Perry, 2001; Reed et al., 2008). While processes of marsh accumulation add mineral sediment and organic matter from the marsh surface, postdepositional compaction of the sediment column is associated within the continuous lowering of the marsh platform (Allen, 1999). Hence, the balance between accretion and compaction-related subsidence determines the elevation of the marsh relative to the tidal frame.

Storm-elevated tides in combination with wave-generated currents mobilize and deposit great quantities of sediment (Stumpf, 1983). For example, a single large storm can deposit a layer of above-average grain size on the marsh surface and may act as the only means of accretion to the high marsh which is rarely inundated by normal spring tides (Stumpf, 1983). Rainstorms mobilize sediment on exposed surfaces and redistribute it to other locations within the marsh (Torres et al. 2003). At the same time, wave and tidal current erosion can damage marshes and undo many of the beneficial effects of storm sediment deposition.

The radionuclides ²¹⁰Pb and ¹³⁷Cs are frequently used to study processes and rates of accretion in tidal marshes, and previous workers have applied ²¹⁰Pb and ¹³⁷Cs geochronology to the study of Delaware Estuary marshes (Church et al. 1981; Orson et al., 1992; Kraft et al., 1992; Kim et al., 1997; Nikitina et al., 2000; Kim et al., 2004; Church et al., 2006). In estuarine waters, dissolved radionuclides adsorb to finegrained suspended sediments, especially clay-sized particles, after which they are transported with suspended particulates. ²²⁶Ra present in the Earth's crust decays to ²²²Rn, which escapes to the atmosphere and decays to ²¹⁰Pb, which returns to the Earth's surface by precipitation and dry deposition (Robbins, 1978). ¹³⁷Cs has no natural source; its presence in the atmosphere is primarily due to atmospheric nuclear weapons testing starting in the 1950s and continuing through the mid-1960s (Graustein and Turekian, 1986; Ritchie and McHenry, 1990). Additional ¹³⁷Cs is delivered to the atmosphere and aquatic waters through periodic release by nuclear reactors (Ritchie and McHenry, 1990). Whereas the atmospheric flux of ²¹⁰Pb is relatively constant, ¹³⁷Cs was delivered in a large pulse between the early 1950s and mid 1960s and then at much lower rates until the mid-1980s (Ritchie and McHenry,

1990) after which atmospheric deposition was negligible. Upon being deposited, downcore distributions of these radionuclides can be used to determine rates of sediment accumulation and marsh accretion and also develop sediment chronologies for the sediment column (DeLaune et al., 1983; Sharma et al., 1987; Bricker-Urso et al., 1989; Appleby and Oldfield, 1992; Benoit et al., 1999; Harvey et al., 2007). Additionally, comparison of measured and predicted inventories of ²¹⁰Pb and ¹³⁷Cs can provide insight regarding pathways of radionuclide and fine-sediment transport. For example, lateral transport and deposition of particle-borne radionuclides in marshes can preferentially focus radionuclides to sites of rapid accumulation, thereby increasing radionuclide inventories above levels that could be supported by local atmospheric deposition or vertical flux from the water column. By comparing measured radionuclide inventories in marsh sediments with expected values it is possible to determine whether the sediment column is accretionary, non-depositional, or erosional (e.g., DeLaune et al., 1994).

1.2 Anthropogenic Activities in Salt Marshes

Humans have impacted salt marshes since the beginning of colonization along the U.S. Atlantic Coast (Kraft et al., 1992; Kennish, 2001; Gedan et al., 2009). Channel deepening and dredging in tidally-influenced systems can increase the tidal prism, allowing for greater penetration of down-estuary waters into up-estuary environments during flood tides. Also, the amount of sediment available for marsh surface accretion can decrease with channelization, because deepening creates a new, lower-energy environment within which fine-grained sediments will preferentially accumulate (Dyer, 1986; Kennish, 2001). Salt marsh vegetation has a long history of both commercial and domestic utility, including use for roof thatch, packing insulation and as a premium livestock feed (Gedan et al., 2009). In order to maximize crop yield, restricting tidal access to the marsh surface allowed high-marsh vegetation to be harvested in low-lying areas that are otherwise flooded too regularly for high-marsh plants to colonize and survive (Gedan et al., 2009). Other forms of tidal and flood-restricting devices such as dams, dikes and weirs have been installed in marshes with similar results. Controlling when tides enter the marsh reduces the amount of mineral sediment accreting on the marsh surface, which can lead to subsidence if continued for too long (Kuhn et al., 1999; Kennish, 2001). At the opposite end of the spectrum, ponding can occur when water is allowed to sit on the marsh surface for long periods of time. This can happen naturally or by purposeful human activities such as for salt production. Excessive flooding and ponding cause stress on the vegetation and will lead to plant mortality in affected areas if water depth is sufficient and plant species are not acclimated to partial or whole submergence (DeLaune et al., 1994).

Due to the expansive areas of flat, open land, marshes were viewed as potentially useful real estate and were reclaimed and converted to cropland for agriculture and grazing fields for livestock. Marshes were filled in, stabilized and used for construction of coastal property. Some of the most populous cities in the world are built on stabilized marshland, for example New York City, Chicago, Mumbai, India and Shanghai, China. In places where marshes were not viewed as useful pieces of real estate they were used as dumping grounds and runoff sites for sewage and industrial waste (Kennish, 2001; Gedan et al., 2009). This resulted in many acres of wetland being polluted with heavy metals and various industrial

chemicals, which are toxic to marsh flora and fauna and require substantial cleanup in order to restore the original marsh ecosystem. Such was the case in Hammonasset Beach State Park in Madison, Connecticut where years of channelization, ditching and colonization by invasive species required 6 years of work by the EPA to restore the salt marsh to a more "natural" state (Roque Jr., 2002).

1.3 The Murderkill River Estuary

This study was conducted in tidal marshes of the Murderkill River estuary in Kent County, Delaware and was part of a much larger study investigating the hydrological and chemical effects of the Kent County Wastewater Treatment Facility on the Murderkill River since construction in the mid-1970s. The mouth of the Murderkill River is located approximately 40 km northwest of Lewes, Delaware and meets Delaware Bay at the town of Bowers Beach, Delaware. Spring Creek, a large tributary, joins the mainstem Murderkill from the northwest at the town of Frederica, Delaware (Figure 2). The Murderkill River has a watershed area of approximately 275 km² and is 34 km long inclusive of the Spring Creek tributary (DeWitt and Daiber, 1974; EPA, 2005). Dams limit the extent of tidal influence upriver (Figure 2). It is thought these dams were constructed to create old mill ponds prior to 1900, but more information is needed to determine the exact dates and purpose of construction. The tidal freshwater segment extends from the dams to the town of Frederica, 12 km above the estuary mouth, and between Frederica and the mouth the waters are brackish. The Murderkill River estuary is fed mainly by freshwater drainage from McGinnis Pond and Andrews Lake on the Spring Creek tributary and by Coursey Pond and McCauley Pond on the mainstem Murderkill (Figure 2). Bayward of

Frederica, 94 % of the tidal river and estuarine basin is bordered by tidal marshes (EPA, 2005). Land use in the Murderkill River watershed is characterized by agriculture (55%), wooded/forest (17%), wetlands (6-9%), urban areas (14%) and open water (<2%) (DNREC, 2005).

The Murderkill River estuary has an average tidal range of 1.6 m at its mouth making it a microtidal estuary (tidal range < 2m). Hydrographic surveys of the Murderkill were performed in the middle 1970s by DeWitt and Daiber (1974) who first showed that the estuary exhibits characteristics of both a well-mixed and partially-mixed estuary. The estuary flushing time is short at 4.4 tidal cycles during mean runoff (DeWitt and Daiber, 1974). Near Bowers Beach the estuary mouth is occupied by brackish water (15.7 to 28.2 ‰) from lower Delaware Bay, which enters the lower estuary during flood tide (DeWitt and Daiber, 1974). The salinity gradient typically extends from mouth to 12 km near Frederica, where salinity decreases to ~1.0‰ during times of low river discharge (DeWitt and Daiber, 1974). In the tidal freshwater reach, salinity does not exceed 1.0 ‰. During ebb tides, salinity in the lower estuary is reduced substantially, and the mean along-channel salinity gradient is 2.4 ‰ per km (DeWitt and Daiber, 1974). A study by Wong et al. (2009) concluded that the principal lunar semidiurnal tide (M_2) is by far the most important tidal influence in the Murderkill River estuary and that the tides are weakly ebb-dominant (shorter, stronger ebb tide). They also concluded that tides are weakened upon entering the Murderkill River; the tide range decreases by 67 % between the estuary mouth and Frederica (Wong et al., 2009). The effluent output of the wastewater treatment facility is not considered a significant hydrological factor when it comes to sediment transport (Velinsky et al., 2010).

Although there have been no prior studies of marsh accretion in the Murderkill River estuary, previous workers have quantified marsh accretion rates elsewhere along the tidal wetland coast of Delaware. For example, Khalequzzaman (1989) computed a mean accretion rate of 0.41 cm yr⁻¹ (seven core average) averaged over the last 100 years near Port Mahon (~15 km north of Murderkill). Kraft et al. (1992) computed a rate of 0.20 cm yr⁻¹ over the last 100 years from one core from South Bowers, and Sommerfield and Madsen (2003) computed an accretion rate of 0.80 cm yr⁻¹ for one core in Blackbird Creek (~35 km north of Murderkill). Nikitina et al. (2000) synthesized earlier work on marsh accretion in the region and computed a median rate of 0.35 cm yr⁻¹ for 28 cores from sites spanning the lower tidal wetland coast of Delaware.

1.4 Mosquito Ditching in Murderkill River Estuary Marshes

In the early Twentieth Century, attempts were made to reduce mosquito populations in coastal marshes in most eastern U.S. Atlantic states (Kennish, 2001; Gedan et al., 2009; Koch and Gobler, 2009). Mosquitoes prefer to lay eggs in calm, stationary waters like those found on marsh platforms when tides flood over the river bank (Hardenburg, 1922). Much of this work was completed by the Civilian Conservation Corps, a public relief program for unemployed men during the Great Depression. In coastal Delaware, the ditches were constructed in tidal marshes from 1933-1937 and were cleaned regularly until the late 1960s (DELDOT, 1963). The premise was to connect the marsh interior to the river channel with rows of parallel ditches, which allow drainage via tidal circulation and flush the marsh interior twice daily (Hardenburg, 1922; Resh and Balling, 1983). By the late 1930s approximately

90% of the original tidal wetlands from Maine to Virginia had been ditched to some degree. At the time it was believed that removing standing water on the marsh would reduce habitat for mosquito larvae. However, it is now known that mosquito-eating fish living within standing water on the marsh are a more effective means of mosquito larvae control than ditching and that ditching caused the destruction of habitat of these fish (Adamowicz and Roman, 2005; Koch and Gobler, 2009).

Ditching of Murderkill River marshes was initially undertaken in 1934-35 (Corkran, 1937). The original schematics indicate that typical ditches in the Murderkill River estuary were constructed to be 10 inches (25.4 cm) wide and 20 inches (50.8 cm) deep, though wider and deeper ditches were constructed as well (Corkran, 1937). It is unknown if these dimensions changed when engineers returned in 1963 to clean the ditches, but field observations suggest ditch geometry remained roughly the same. It is impossible to know which ditches were cleaned and which were not because detailed records of the 1963 cleaning process do not exist. Ditches are still noticeable features in aerial photographs and on foot because they are bordered by dense, high-stand Spartina alterniflora whereas the inter-ditch area is occupied by low-stand S. alterniflora and S. patens.

The effects of ditching on tidal flow and marsh sedimentation are not well understood. In a study of tidal marshes in Port Mahon, Delaware, sedimentation rates appear to have increased by about 0.1 cm/yr over the long-term (100-yr) average following the ditching program (Khalequzzaman, 1989). In that study it was suggested that the increase in sedimentation rates was due to the fact that sediment removed from the ditches was dumped along the banks in the ditches, providing a local source of material for redeposition on the marsh platform rather than a change in

hydrodynamics (Khalequzzaman, 1989). Hence, prior to the present study there was some evidence to suggest that the mosquito ditches impact natural processes of accretion in Delaware Estuary salt marshes.

1.5 Research Goals and Hypotheses

The goals of this study were twofold: 1) to determine the spatial variability of sediment accumulation and marsh accretion rates within the greater estuarine segment of the Murderkill River; and 2) to investigate the specific effects of mosquito ditching on accumulation and accretion rates in a section of the lower estuary for insight into ditching impacts in general. This was accomplished by collecting sediment cores from non-ditched and ditched areas of the marsh, including cores from the ditches themselves and between ditches and comparing the physical properties and radionuclide content of the sediment column.

Based on a general knowledge of marsh sedimentation processes and available cases studies of ditched marshes (Khalequzzaman, 1989; Adamowicz and Roman, 2005; LeMay, 2007; Koch and Gobler, 2009), it was hypothesized that the ditches should initially starve the adjacent marsh platform of mineral sediment while the ditch fills to an equilibrium elevation. Upon reaching equilibrium, the hydraulic conveyance provided by the ditches should increase the tidal hydroperiod and supply a larger amount of suspended matter to the marsh interior compared to an unditched marsh. The conceptual model of marsh sedimentation (Figure 1) dictates that sediment is deposited in the marsh interior mostly when the platform is flooded on spring tides, when the tide rises above the channel bank. The corollary is that

tide level. However, by connecting the marsh interior to a source of sediment in the estuarine channel, the ditches should increase rates of mineral sediment accumulation and accretion in the marsh interior relative to a comparable non-ditched marsh.

Chapter 2

METHODS

2.1 Marsh Core Sampling

Sediment cores were collected at a total of ten locations using a tripod in conjunction with 10-cm diameter PVC pipe tipped with a core "catcher" designed to prevent the core from slipping out upon extraction of the pipe from the subsurface. Coring locations are shown in Figure 3, and site details are listed in Table 1. Two cores were collected at each site: 1) cores labeled "A" were split lengthwise, described visually and photographed, sealed in plastic, and stored in a refrigerator at the School of Marine Science and Policy; and 2) cores labeled "B" were extruded vertically in the laboratory and the material processed for radionuclide and sedimentological measurements. Cores at sites MK-1 through MK-4 were collected in non-ditched parts of the estuary, along the salinity gradient of the Murderkill River estuary to characterize sediment accumulation in undisturbed marsh (Figure 3). These cores were collected initially to meet the objectives of a study designed to determine the historical record of nutrient loading in the Murderkill River (Velinsky et al., 2010). Cores at sites MK-5 through MK-10 were collected in an area of the lower estuary where the marsh was ditched in 1934-1935 and again in 1963 (Figure 3) (Corkran, 1937). Cores MK-5B, MK-7B, and MK-9B were collected on the marsh platform between ditches (inter-ditch core), whereas cores MK-6B, MK-8B, and MK-10B were collected within open ditches (ditch core). Marsh elevation data for the coring sites relative to NAVD88 were provided by Dr. Thomas McKenna, Delaware Geological

Survey. Elevations using LIDAR are listed in Table 1 have an RMS error of 0.15 m. The resolution of the LIDAR data used for this purpose was insufficient to determine elevations within the ditches themselves, but they were estimated to fall \sim 0.2 m below the immediately adjacent marsh surface elevation.

2.2 Bulk Sediment Properties

To determine bulk sediment properties of the core material, every other 2cm thick interval extruded from cores was weighed wet (W_{wet}), dried at 100°C for 24 hours in a convection oven, and weighed again dry (W_{dry}). Porosity (\emptyset) was computed gravimetrically from water content (W_c) using assumed values for mineral density ($\rho_m = 2.65 \text{ g cm}^{-3}$) and fluid density ($\rho_w = 1 \text{ g cm}^{-3}$) as follows:

$$\emptyset = \frac{W_c \rho_m}{W_c \rho_m + (1 - W_c) \rho_w} \tag{1}$$

where $W_c = (W_{wet} - W_{dry}) / W_{wet}$. Dry bulk density (ρ_d) was computed from porosity following:

$$\rho_d = (1 - \emptyset)\rho_m \tag{2}$$

In this method it is assumed that the density of mineral grains and organic matter is the same.

Dried sediment was pulverized using a mortar and pestle and packed in 60-ml volume plastic jars for radionuclide analysis. A 4-g subsample of the powder was later combusted in a muffle furnace at 550°C for four hours to determine percent organic matter content by loss-on-ignition (LOI) according to methods described in Heiri et al. (2001). LOI data can be used as a means of determining the maximum depth to which ditching penetrated the marsh platform. A ditch will begin to fill in with predominantly mineral sediment once it has been dug, because the depth of water and rapid infilling prohibit any kind of vegetative growth. For example, a core collected in a filled-in ditch should show a thick interval of mineral-rich sediment with lower LOI values above sediment with higher LOI values representative of the original marsh. Similarly, infilled ditches should have lower LOI values compared to the adjacent marsh platform where roots and organic materials are living and decaying.

To observe changes in the composition of the sediment column through time at the coring sites, it was necessary to compute the specific contributions of mineral matter, organic matter, and water/entrapped gas to the total sediment volume. To accomplish this, Equation 1 was modified to account for the densities of mineral and organic solids. Plant biomass and organic-rich sediment are effective mediums for trapping water and gas, and in general porosity increases with increasing LOI (e.g., DeLaune et al., 1978). The specific porosity was computed as follows:

$$\phi_{S} = \frac{W_{c} \left(\left(1 - \frac{LOI}{100} \right) * \rho_{m} + \frac{LOI}{100} * \rho_{o} \right)}{W_{c} \left(\left(1 - \frac{LOI}{100} \right) * \rho_{m} + \frac{LOI}{100} * \rho_{o} \right) + (1 - W_{c}) * \rho_{w}}$$
(3)

where $Ø_s$ is the specific porosity, ρ_o is the organic density (1.2 g cm⁻³), and the remaining terms are defined above. The value for organic density is an average of different values reported in the scientific literature (DeLaune et al., 1978; DeLaune et al., 1983). Equations 1 and 3 produce comparable porosities within 5%, but Equation 3 allows for separation of the sediment constituents. The total volume of the sediment column (V_t) is composed of water and gas (V_w), mineral solids (V_m), and organic solids (V_o) as described by:

$$V_t = V_w + V_m + V_o = 1$$
 (4)

where $V_w = \emptyset_s$, $V_m = (1 - LOI/100)(1 - \emptyset_s)$, and $V_o = (LOI/100)(1 - \emptyset_s)$.

2.3 Grain-size Measurements

Grain size is a key parameter in estuarine sediment transport. In this study downcore measurements of disaggregated grain size were made to shed light on potential changes in the marsh hydrodynamic environment over time. Additionally, because radionuclides preferentially bind to fine-grained sediment, grain-size data can aid the interpretation of radionuclide profiles (Ritchie and McHenry, 1990). Three grain-size fractions were examined: $< 2 \mu m$ (clay), 2-10 μm (fine silt) and 10-63 μm (course silt). In estuarine and marine waters sediment grains smaller than 10 μm in diameter are almost always present as flocs, whereas larger silts are transported most as single grains, although they can still form mudflocs (McCave et al., 1995). The 10-63 μm fraction is referred to as "sortable silt" because this fraction can be hydraulically sorted and thus provide information on conditions of hydrodynamic flow in the bottom boundary layer (McCave et al., 1995).

Disaggregated grain-size analysis was performed on core material using a Beckman-Coulter Multisizer 3 (coulter counter), which is a standard method in marine sedimentological studies (e.g., Bianchi et al., 1999). Small (< 0.4 g) subsamples of sediment extruded from the "B" cores were wet-sieved through a 63- μ m sieve into a jar using a solution of 0.05% sodium metaphosphate solution and allowed to sit overnight. Sodium metaphosphate is a deflocculant and acts to break up aggregations of fine-grained sediment that would otherwise skew the measured distribution towards larger grain sizes. Particles larger than 63 μ m in size were removed from the sieve, placed into pre-weighed metal dishes and dried overnight. This sand-sized material

consisted mostly of organic debris with some large mineral grains, and in this study was not examined in detail.

Prior to analysis, the solutions were agitated with a sonifier/cell disruptor for one minute, and then a metal stir bar was added to stir the solution during analysis to prevent any settling. Coulter-counter aperture tube sizes 70 (suitable for grain sizes 1.4-42 μ m) and 140 (suitable for grain sizes 2.8-84 μ m) were used to capture the grain size spectrum. Since the Multisizer 3 requires very low particle concentrations, 25-35 ml of Isoton II (a charged dilutant) was added to the test solution 1-5 ml Each sample was run three times per aperture tube for a total of six runs per sample, and the results of the runs were averaged to produce a total grain size distribution. Given a sediment density (2.65 g cm⁻³ for the present samples), the Multisizer calculates the cumulative mass frequency distribution of grain sizes for each sample. Repeated clogging of the aperture prevented use of apertures sizes smaller than 1.4 μ m in this study, so the 1.4-42 μ m spectrum was extrapolated to 0.5 μ m through the use of an exponential growth function computed for each sample in order to obtain the full spectrum of interest.

2.4 Radionuclide Measurements

Radionuclide analysis of dried, homogenized sediments was performed by gamma spectrometry following established methods (e.g., Wallbrink et al., 2002). Samples for radionuclide analysis were placed in a 60-ml plastic jar and counted for 24 hours using Canberra Model 2020 low-energy Germanium (LEGe) detectors to determine activities of ²¹⁰Pb, ²¹⁴Bi, and ¹³⁷Cs. ²¹⁰Pb was determined by measuring the activity of ²¹⁴Bi, a short-lived granddaughter of ²²⁶Ra assumed to be in secular equilibrium with its parent. The sediment-depth distributions of these radionuclides

are used to calculate sediment accumulation rates, marsh accretion rates, and radionuclide inventories. In this study "accumulation" refers to a mass accumulation rate (g cm⁻² yr⁻¹) whereas "accretion" denotes a linear sedimentation rate (cm yr⁻¹). Conceptually, accumulation of mineral and organic material drives vertical accretion of the marsh on the long term. Accumulation occurs by material deposition on the marsh surface, and in the case of organic matter, through burial of belowground plant biomass. A marsh can accrete locally, but if the landscape is subsiding as fast or faster there may be no net elevation change or net subsidence. The radioisotope inventory represents the depth-integrated activity of a radioisotope in units dpm cm⁻².

2.5 Radionuclide Models and Accumulation Rate Determination

Sediment dating methods used in this study rely on the assumptions that the specific activity or flux of ²¹⁰Pb deposited at the marsh surface is constant through time (steady state), and that ¹³⁷Cs deposition follows its atmospheric source function with an onset of 1954 and peak fallout in 1963 (Olsen et al., 1985; Graustein and Turekian, 1986). Additional assumptions for sediment chronometry with radioisotopes are as follows: biological mixing (burrowing, bioturbation) and other post-depositional processes have not enhanced particle burial; the radionuclides are chemically nonreactive and immobile upon burial, and the sedimentary record is complete and not punctuated by non-depositional or erosional episodes. The latter assumption is still considered valid even though the ditched sites of the study area have a documented history of disturbance.

In the case of ²¹⁰Pb, the *constant initial concentration* model (CIC) specifies constant initial activity (dpm g⁻¹) of excess ²¹⁰Pb in surface sediment samples

and a constant influx rate of sediment (Robbins, 1978; Appleby and Oldfield, 1992). In other words, variations in mineral deposition rate do not alter the initial concentration of excess ²¹⁰Pb, but the flux of ²¹⁰Pb to the sediment varies with mineral deposition. The CIC model is described by:

$$A_z = A_0 \exp\left(-\frac{\lambda z}{S}\right) \tag{5}$$

where A_0 is the radionuclide specific activity at surface (dpm g⁻¹ of bulk sediment), A_z is the radionuclide specific activity at depth z, λ is the decay constant for ²¹⁰Pb (0.0311 y⁻¹), z is sediment depth (cm), and S in the accretion rate (cm yr⁻¹) averaged over the full profile of excess activity. The accretion rate can be solved for directly from:

$$S = \frac{\lambda z}{\ln \left(\frac{A_0}{A_z}\right)} \tag{6}$$

At steady state, a profile of the log of excess ²¹⁰Pb versus depth or cumulative mass should form a straight line over the full profile of excess activity where the slope of a regression line through all points is equivalent to the accretion rate. This ²¹⁰Pb technique is best-suited to environments where the sedimentary record is relatively complete (e.g. Orson et al, 1992).

The *constant rate of supply* model (CRS) is another method for calculating sediment accretion rates from ²¹⁰Pb profiles (Robbins, 1978; Appleby and Oldfield, 1992). The CRS model specifies that the flux of ²¹⁰Pb to the sediments is constant and implies that the excess inventory is supported by atmospheric deposition alone. The age of a sediment layer and the mass accumulation rate of the sediment column are proportional to the inventory of excess ²¹⁰Pb below a reference depth, thus the full profile of excess ²¹⁰Pb in the sediment must be determined. Unlike the CIC model, which is more commonly used to provide a single depth-averaged

accumulation or accretion rate, the CRS model can be used to determine how the rate of accumulation has varied over time (depth). As discussed later, excess ²¹⁰Pb inventories in the Murderkill River marsh were found to exceed the theoretical inventory supported by the atmospheric flux, suggesting that additional ²¹⁰Pb is supplied by tidal waters. The CRS model works best for environments that only receive radionuclides atmospherically and not from lateral transport. Therefore the CRS model was not used in this study because the underlying assumption could not be met. Ages of sediment calculated after excess ²¹⁰Pb was exhausted are extrapolated using the linear CIC rate to determine age.

Sediment chronometry with ¹³⁷Cs is based on the shape of the activitydepth profile and the 1954 (onset) and 1963 (peak fallout) reference dates. Assuming there has been no post-depositional mixing of the sediment column (e.g. bioturbation), dividing the depth of first occurrence (or peak) of ¹³⁷Cs in the sediment column sediment by the number of years between the reference date and the year of core collection gives the accretion rate:

$$S = \frac{L}{T_2 - T_1} \tag{7}$$

where S (cm yr⁻¹) is the sediment accumulation rate, L (cm) is the depth of measurable ¹³⁷Cs activity below the surface, T_1 (yr) is the year of ¹³⁷Cs onset (1954) or peak fallout (1963) in the environment, and T_2 (yr) is the date of core collection. The advantage of the ¹³⁷Cs technique over the ²¹⁰Pb method is that it more closely provides the absolute age of sediments deposited after 1954, because it is based on fallout events rather than ages computed from radioactive decay.

Sediment inventories of ²¹⁰Pb and ¹³⁷Cs were calculated in order to determine the total amount of radionuclide buried at the coring sites. The radionuclide inventory is calculated as follows:

$$I_o = \Sigma_i \rho_{di} x_i A_i \tag{8}$$

where I_0 is the radionuclide inventory (dpm cm⁻²), ρ_d is the bulk density, x is the sediment interval thickness (cm) and A is the activity (dpm g⁻¹) where i indicates the ith interval in the core. Following the CIC ²¹⁰Pb model, at steady state (no temporal variation in A_0), the excess inventory should increase proportionally with increasing sediment accumulation rate.

Mass accumulation rates (MAR) describe the flux of sediment through a unit area of marsh surface and can be determined independently for mineral and organic matter constituents. One method for computing MAR involves knowing the dry-bulk density for each interval in order to calculate the total (inorganic plus organic) cumulative mass for the core. Bulk cumulative mass is given by:

$$CM_i = \Sigma_i \rho_{di} x_i \tag{9}$$

where CM_i is the cumulative mass, ρ_{di} is dry-bulk density (g cm⁻³), x_i is the interval thickness (cm) and i is the ith interval of the core. In this study sediments from every other 2-cm interval of the sediment column were analyzed, so to interpolate between intervals a cubic spline was used. Cumulative mass was calculated to the depth when excess ²¹⁰Pb reached zero (*N*) and was used in place of depth (*z*) in Equation 6 to calculate MAR based on excess ²¹⁰Pb (MAR_P):

$$MAR_P = \frac{\lambda N}{\ln \left(\frac{A_0}{A_N}\right)} \tag{10}$$

where A_N is the excess ²¹⁰Pb activity at the same depth as *N*. For comparison, ¹³⁷Csbased mass accumulation rates (MAR_C) were calculated using the same steps as described for Equation 7 but depth (*L*) is replaced with *CM_i*:

$$MAR_C = \frac{CM_i}{T_2 - T_1} \tag{11}$$

Radionuclide focusing in the marsh was determined from the ratio of the measured inventory and a reference inventory supported by atmospheric deposition. Focusing is the process by which particle-reactive materials are preferentially sequestered at one depositional site over another as a consequence of particle transport or localized scavenging processes. Focusing of radionuclides can occur in three ways: 1) when sediments with the same radionuclide activity accumulate preferentially in one spot at the expense of another; 2) when radionuclide-laden sediment is eroded from one place and deposited in another; and 3) when dissolved-phase radionuclides sorb to resuspended sediment and are concentrated. This final method is a way for radionuclides to become focused without focusing sedimentary particles because sediment can resuspend and redeposit in the same location. Because radionuclide focusing is frequently a consequence of sediment transport processes, variations in focusing factors among marsh depositional sites can shed light on preferred pathways of fine-sediment and contaminant transport. Focusing factors were computed as follows:

$$FF = \frac{Q_{measured}}{Q_{reference}} \tag{12}$$

where FF is the focusing factor and Q is radionuclide inventory. A focusing factor greater than unity implies that radionuclide activity has been preferentially transported or "focused" from one location to another by a combination of hydrodynamic flow and

sedimentary processes. Conversely, a focusing factor less than unity implies that the atmospheric flux is not sequestered locally perhaps on account of sediment erosion and redistribution. Reference inventories of 28 dpm cm⁻² for ²¹⁰Pb and 21 dpm cm⁻² for ¹³⁷Cs have been determined through prior work from direct measurements of radionuclide atmospheric deposition in the U.S. mid-Atlantic region (Olsen et al. 1985; Graustein and Turekian, 1986). These reference inventories were used in the present study of the Murderkill River marsh.

Chapter 3

RESULTS AND INTERPRETATION

3.1 Sediment Properties

Cored sediments for the non-ditched areas of the marsh consisted mostly of clayey silt with variable quantities of living and dead plant material. Each core displayed a slightly different dry bulk density (DBD) depth profile. Values ranged from 0.11 to 0.76 g cm⁻³ (Figures 4-13; Appendix B). In a compositionally uniform sediment column, bulk density generally increases with depth as compaction over time reduces porosity and porewater is expelled. This general trend was evident in only a few cores, and many cores exhibited an opposite decreasing trend presumably due to variations in organic matter and grain size with depth. Core MK-1B showed a variable but overall decreasing bulk density trend to ~45 cm depth after which values remained relatively uniform to the bottom of the core (Figure 4). MK-2B initially increased with depth to ~42 cm but then decreased to near-constant values toward the core bottom (Figure 5). MK-3B showed some variance in bulk density but was essentially uniform with depth to 80 cm, but values increased sharply to the bottom at 100 cm (Figure 6). Bulk density was most variable in MK-4B, ranging from 0.30 to 0.76 g cm⁻³ with no discernible gradient with depth (Figure 7).

Cores from the ditched area of the marsh exhibited a more narrow range of dry bulk density values with depth (0.16 to 0.56 g cm⁻³). Ditch core MK-6B had an almost linear decrease with depth (Figure 9), whereas ditch core MK-8B had uniform bulk density values down to an abrupt decrease in density near 52 cm (Figure 11).

Similarly, ditch core MK-10B varied little with depth to 60 cm, below which it decreased gradually to 80 cm (Figure 13). Inter-ditch cores MK-5B and MK-9B displayed no gradients in bulk density with depth (Figures 8 and 12, respectively), but in core MK-7B bulk density decreased gradually from the core top to 40 cm after which it was uniform to the core bottom (Figure 10).

The organic matter content of all cores based on the LOI measurements ranged from 9.6 to 71% by weight (Figures 4-13; Appendix B). LOI values were highest in cores from sites MK-1B and MK-2B, particularly in the lower sediment column where values reached ~70% (Figures 4 and 5). MK-1B and MK-2B displayed distinct shifts in LOI upcore beginning at ~45 cm depth to go along with equal shifts in DBD, as previously mentioned. Cores MK-3B and MK-4B exhibited weakly decreasing LOI from the core top to bottom (Figures 6 and 7). The organic content of inter-ditch core MK-5B increased from the core top to ~10 cm depth, but then decreased to uniform values to the bottom (Figure 8). MK-7B had a weak increasing trend from 0 to 30 cm depth followed by no net trend to 100 cm (Figure 10). MK-9B organic content decreased very slowly with depth throughout the entire core (Figure 12).

There was a statistically significant (P < 0.0001) linear relationship between organic matter content and dry bulk density in which LOI varied inversely with dry-bulk density (Figure 14). This suggests that the values of bulk density measured in cores are partly a function of the concentration of organic material in the sediment column. Considering that the particle density of organic matter (1.2 g cm⁻³) is less than that of mineral sediment (2.65 g cm⁻³), more organic material relative to mineral sediment will decrease the dry-bulk density of the sediment column. Also,
live plant matter such as roots, stems, and rhizomes does not compact as completely as mineral sediment, and can create a matrix of void space for the entrapment of water and gas. Similar relations between marsh sediment bulk density and organic matter content have been reported by DeLaune et al. (1994).

Changes in LOI were used to identify the maximum extent that ditches penetrated the marsh platform. Of the three ditch cores collected for this study, only MK-8B showed convincing evidence for a shift on LOI concordant with mineral mud filling in atop relict marsh sediment with higher organic content (Figure 11). MK-8B exhibits a transition at 50-57 cm and which corroborates the historical record of ditching practices in the Murderkill River marsh. This observation is not present in cores MK-6B or MK-10B, perhaps either because 1) the cores did not penetrate past the maximum depth of ditch construction; 2) these sites have always been dominated by mineral accumulation; or 3) some mix of new mineral mud and ditch spoil material filled in at the bottoms of these sites.

3.2 Volumetric Composition of Marsh Sediment

As shown in Figures 15–24, Murderkill River marsh cores are composed of 85% water and entrapped gasses by volume, on average. The relative contributions of organic and mineral solids to total volume reveal that average mineral volumetric content generally increases toward Delaware Bay. On the basis of sediment source only, this implies that marsh depositional sites proximal to Delaware Bay trap larger percentages of mineral matter than more distal sites. This provides some evidence that Delaware Bay supplies suspended sediment tidally to the Murderkill River estuary. The relative volume of organic solids is nearly constant throughout all ten cores,

suggesting that the organic contribution to the marsh sediment column has been nearly constant over the past century.

The volumetric composition of cores exhibited a range of downcore (temporal) patterns. In core MK-1B (Figure 15) greater quantities of mineral matter were preserved at intervals concordant with ca. 1950 and ca. 1980. In cores MK-1B (Figure 15), MK-2B (Figure 16), MK-7B (Figure 21) and MK-8B (Figure 22) significant increases in mineral solids correspond to increases in clay content, most notably in cores MK-1B and MK-7B. Nine out of the ten cores have mineral volumes that greatly exceed the organic volume, the only exception being MK-2B, which is nearly half mineral and half organic matter from top to bottom (Figure 16). Ditch cores MK-8B and MK-10B show clear increases in mineral accumulation at depths of 58 cm and 60 cm, respectively which correspond to the maximum depth of ditching (Figures 22 and 24, respectively). Inter-ditch core MK-7B has a distinct increase in mineral volume starting at ~40 cm depth (ca. 1930) to the core top (Figure 21), and MK-5B shows evidence of decreasing mineral volume and increasing organic volume beginning around ~25 cm depth (ca. 1935) (Figure 19), suggesting that mosquito ditch construction may be related to the changes in these sites. MK-9B does not contain any discernible downcore trends in volume composition (Figure 23).

3.3 Grain-size Distribution

Grain-size distributions of the mud fraction only are reported as mass percent sortable silt (10-63 μ m), fine silt (2-10 μ m) and clay (< 2 μ m). In general, the cored sediment column from all sites consisted of fine silt and sortable silt (Figure 26). All six cores in the ditched area show remarkably similar grain size distributions that

were generally ~65% fine silt by mass, ~25% sortable silt, and ~10% clay. MK-7B is the only ditch-area core with marked variation in grain size: a trend of increased clay and fine silt percentages beginning at 48 cm to the core top (Figure 21). Cores MK-1 and MK-2 upriver contained more sortable silt and less clay than cores MK-3 and MK-4 (Figure 25). Core MK-1B showed a shift in dominant grain size upcore beginning at ~45 cm, where the dominant grain size fraction changes from sortable silt to fine silt (Figure 15). Sorting and median diameter values for all cores indicate a poorly sorted ($1 < \varphi < 1.5$) mud fraction and median grain sizes between 7.9 and 5.9 φ (4-16.7 µm) (Figure 27). This range of sorting is observed for every core, but cores MK-1B and MK-2B contain the largest median grain size values of all. Core MK-4B has median grain size and sorting values identical to those of cores collected acrossriver in the ditched marsh. Interestingly, there appear to be no differences in median grain size and sorting between cores from the ditches and cores obtained on the adjacent, inter-ditch marsh platform (Figure 27).

Simple regression analysis was used to identify relationships between the grain-size properties and organic matter content (LOI) of the sediment column. LOI positively correlates with sand and sortable silt content, but negatively with fine silt and clay (Figure 28); in all cases the correlation is statistically significant (P < 0.0001). These results suggest that the organic fraction of the sediment is in some manner associated with cohesionless sands and sortable silts as opposed to cohesive fine silts and clays. If most of the organic matter preserved in the sediment originated as detrital particulates (as opposed to belowground plant biomass), then the relationship between LOI and grain size implies that the particulate organic matter is transported in the form of discrete grains with hydraulic properties similar to sand and

coarse silt. The amount of organic matter at each site appears to be related to the grain size trends in sand and sortable silt: sediment intervals with the highest LOI values contain the largest percentage of sand or sortable silt (Figure 28, panels A and B). While this correlation could be explained by greater quantities of below-ground organic material growing in the larger and more permeable grain sizes, visual examination of the sand-sized fraction after sieving indicated that it consisted mostly of organic debris, not mineral grains. The negative correlation between fine silt and clay with LOI is explainable by the fact that total grain size composition for fine silt, clay and sortable silt is cumulative: if sortable silt increases, fine silt and clay must decrease.

3.4 Radionuclide Profiles and Sediment Accumulation and Accretion Rates

Downcore profiles of excess ²¹⁰Pb and ¹³⁷Cs activity are shown in Figures 4–13, and sediment accumulation and accretion rates derived from these profiles are listed in Table 2. The profile of excess ²¹⁰Pb activity for core MK-1B exhibited a log-linear decrease to a depth of 58 cm, indicative of steady-state sediment accumulation and radioactive decay (Figure 4). The measured excess ²¹⁰Pb accretion rate is 0.72 cm yr⁻¹, and the corresponding bulk mass accumulation rate was 0.19 g cm⁻² yr⁻¹. Activities of ¹³⁷Cs increased upcore from the depth of first occurrence at 44-48 cm to a sharp peak at 28-32 cm, above which activities decreased to lower, but detectable, values near the core top (Figure 4). Accretion and mass accumulation rates calculated from the depth of the ¹³⁷Cs activity peak are 0.67 cm yr⁻¹ and 0.20 g cm⁻² yr⁻¹, respectively. The shape of the ¹³⁷Cs profile for this core and for all other cores in the

study area, excluding those collected from ditches, is consistent with the record of ¹³⁷Cs atmospheric fallout in U.S. Mid-Atlantic region since 1954 (Olsen et al., 1981).

Core MK-2B exhibited ¹³⁷Cs and excess ²¹⁰Pb distributions similar to those observed in core MK-1B (Figure 5). Excess ²¹⁰Pb activity extended to 62 cm sediment depth before reaching uniform, non-zero values to the core bottom. This corresponds to an accretion rate of 0.72 cm yr⁻¹ and mass accumulation rate of 0.13 g cm⁻² yr⁻¹. ¹³⁷Cs activities increased upcore from the depth of first occurrence at 44-48 cm to a well-defined peak centered at 28- 32 cm, and then decreased to values near the detection limit at the core top. Accretion and mass accumulation rates computed from the ¹³⁷Cs activity peak are 0.67 cm yr⁻¹ and 0.11 g cm⁻² yr⁻¹, respectively.

Excess ²¹⁰Pb activity in core MK-3B extended to a depth of 50 cm. The decay profile indicates an accretion of 0.57 cm yr⁻¹ and a mass accumulation rate of 0.13 g cm⁻² yr⁻¹ (Figure 6). ¹³⁷Cs activities increased upcore from first occurrence at 32-36 cm to a distinct peak centered at 16-20 cm and thereafter decreased to near-zero at the core top. Accretion and mass accumulation rates based on the depth of the ¹³⁷Cs peak are 0.40 cm y⁻¹ and 0.10 g cm⁻² yr⁻¹, respectively.

Excess ²¹⁰Pb activity in core MK-4B extended to a depth of 36 cm, but with more scatter about the trend line at depth than in core MK-3B, before reaching constant, non-zero values to the core bottom. The accretion rate for core MK-4B is 0.33 cm yr⁻¹ and the mass accumulation rate is 0.14 g cm⁻² yr⁻¹. The first occurrence of ¹³⁷Cs activity in core MK-4B was centered at 20-22 cm, with a broad peak at 8-16 cm (Figure 7). The ¹³⁷Cs accretion and mass accumulation rates for this site are based on the peak middle at 13 cm and are 0.29 cm yr⁻¹ and 0.14 g cm⁻² yr⁻¹. The accretion rates are the lowest among the four non-ditched marsh sites, but the mass

accumulation rates computed from both radionuclides are greater than cores MK-2B and MK-3B, signifying a difference in the type of preserved material at these sites.

Within the ditched area of the marsh, accretion and accumulation rates were comparable to those in the non-ditched areas, but there were significant differences between ditch and inter-ditch depositional sites. Inter-ditch core MK-5B contained excess ²¹⁰Pb activity to a depth of 28-30 cm before reaching near-constant, non-zero values to the core bottom. This corresponds to accretion and mass accumulation rates of 0.32 cm yr⁻¹ and 0.12 g cm⁻² yr⁻¹, respectively. In this core, ¹³⁷Cs first occurred at 32-34 cm, increased in activity to 16-18 cm, and then decreased to near-zero values at the core top (Figure 8). Accretion and mass accumulation rates based on the ¹³⁷Cs peak were 0.37 cm yr⁻¹ and 0.15 g cm⁻² yr⁻¹, respectively.

Inter-ditch core MK-7B contained excess ²¹⁰Pb to a depth of 52-54 cm. ²¹⁰Pb accretion and mass accumulation rates are 0.48 cm yr⁻¹ and 0.17 g cm⁻² yr⁻¹, respectively. ¹³⁷Cs first appeared at 36-38 cm depth, reached a distinct peak at 24-26 cm and then decreases to near-zero values up to the core top (Figure 10). The 1963peak depth corresponds to accretion and mass accumulation rates of 0.54 cm yr⁻¹ and 0.25 g cm⁻² yr⁻¹, respectively.

Inter-ditch core MK-9B displayed a monotonic decrease in excess ²¹⁰Pb to a depth of 24-26 cm, below which activities remained constant for another 10 cm. Accretion and mass accumulation rates are 0.27 cm yr⁻¹ and 0.10 g cm⁻² yr⁻¹ (Figure 12). ¹³⁷Cs first occurred at 24-26 cm depth, increased to a sharp peak at 12-14 cm, and decreased to near-zero values at the core top (Figure 12). The accretion rate based on the ¹³⁷Cs peak is 0.28 cm yr⁻¹ and mass accumulation rate is 0.11 g cm⁻² yr⁻¹. Cores MK-7B and MK-9B exhibited similarly shaped profiles as MK-5B but have less

scatter about the trend line for excess ²¹⁰Pb and have more pronounced ¹³⁷Cs activity peaks.

In contrast to the inter-ditch marsh sites, radionuclide profiles for the ditch sediment column showed evidence of disturbance by ditch construction. The most conspicuous feature is uniform ¹³⁷Cs activity from the depth of first occurrence to the core top; none of the ditch cores exhibited a ¹³⁷Cs peak as was observed at the interditch marsh sites. The last phase of mosquito ditching in the Murderkill River estuary took place in 1963, and aerial photographs from 1937 and 1968 confirm that ditches were present at coring sites MK-6, MK-8, and MK-10 these years. Accordingly, the first occurrence of ¹³⁷Cs in ditch fill sediment should be 1963, assuming the ditches started to accumulate soon after construction. This interpretation also assumes that in 1963 the ditches were re-excavated through strata older than ca. 1954, i.e., not labeled with ¹³⁷Cs. Historical records indicate that ditches in the Murderkill River marsh were excavated to a depth of at least 50 cm (Corkran, 1937), so ¹³⁷Cs activity in the ditch fill should extend down to ≤50 cm. The ditch cores also exhibit a discontinuity in the ²¹⁰Pb profile; excess activity decreases abruptly across the contact between the post 1963-ditch fill and the underlying relict marsh.

Ditch core MK-8B displayed radionuclide profiles consistent with disturbance. The excess ²¹⁰Pb profile decreased gradually downcore to 52-54 cm, below which it decreased suddenly to several units of lower activity. The accretion and mass accumulation rates for this site are 1.05 cm yr^{-1} and $0.44 \text{ g cm}^{-2} \text{ yr}^{-1}$, respectively. ¹³⁷Cs penetrates the sediment column to 52-54 cm at low, uniform activities (Figure 11). Assuming the first occurrence of ¹³⁷Cs is 1963 at this site, the

accretion and mass accumulation rates are 1.15 cm yr⁻¹ and 0.49 g cm⁻² yr⁻¹, respectively.

Ditch core MK-10B exhibited ²¹⁰Pb and ¹³⁷Cs profiles similar to MK-8B, again consistent with disturbance. Excess ²¹⁰Pb activities decreased gradually to a depth of 52-54 cm, below which there was an abrupt decrease. At this site, the accretion rate is 1.04 cm yr⁻¹ and the mass accumulation rate is 0.51 g cm⁻² yr⁻¹. The first occurrence of ¹³⁷Cs is at 56-58 cm depth, where it increases upcore to low but still detectable activities to the core top (Figure 13). ¹³⁷Cs-derived accretion and mass accumulation rates are 1.24 cm yr⁻¹ and 0.61 g cm⁻² yr⁻¹, respectively.

Ditch core MK-6B exhibited both of the radionuclide signatures associated with disturbance. Excess ²¹⁰Pb extended to 78 cm, but there was a sudden decrease after 20-22 cm. Activities deeper than 20-22 cm occasionally reached zero or were below the detection limits, but most values fell between 0.1 and 1 dpm g⁻¹ with no apparent decay pattern. Excess ²¹⁰Pb appeared to reach some range of constant activity after this sudden decrease, and for this reason the interval just prior to the decrease (20-22 cm) was chosen as the lower limit of excess ²¹⁰Pb. The slope of the activity profiles using this interpretation gave accretion and mass accumulation rates of 0.50 cm yr⁻¹ and 0.25 g cm⁻² yr⁻¹, respectively. The first occurrence of ¹³⁷Cs fell at 28-30 cm, but above this the activities were low and uniform to the core top (Figure 9). Assuming that the base of the ¹³⁷Cs profile is concordant with 1963, corresponding accretion and mass accumulation rates are 0.63 cm yr⁻¹ and 0.32 g cm⁻² yr⁻¹, respectively. There are at least three possible explanations for the relatively shallow penetration of ¹³⁷Cs at this site: 1) slumping of old sediment into the ditch, 2) the excavated sediment returned to the ditch after it was placed on the marsh surface in 1963 without scavenging radionuclides from tidal waters, or 3) the ditch was not cleaned to its original depth in 1963. Whatever the case, ¹³⁷Cs does not extend to the same depth as in ditch cores MK-8B and MK-10B, and consequently the accretion and mass accumulation rates are lower.

Elevations at coring sites range from 0.61 to 0.96 m above sea level, nearly a two-fold difference between the highest and lowest sites (Table 2). Elevation above mean tide level is an important factor influencing accretion and mass accumulation, because it influences patterns of sediment delivery to and accumulation on the marsh platform (Allen, 2000; French, 2006). Regression analysis suggests that there is no statistically significant relationship between marsh elevation and mass accumulation rates at the coring sites. This analysis is inconclusive, however, because the LIDAR elevation data available for the study area might not be representative of the actual elevation at the coring sites due to the influence of vegetation.

Perhaps the most significant result of this section is the large disparity in mass accumulation rates between ditch cores and all other sample sites. The largest mass accumulation rates using either radionuclide method correspond to rates from ditch cores (Table 2). Ditch core MARs are between 1.3-5.7 times greater than any MAR from a non-ditched core (Table 2). Combined with the knowledge that ditch sediment is mostly composed of mineral matter (Figures 20, 22 and 24), this reveals that mineral mud has been preferentially trapped in ditches since they were excavated. This is significant mostly because the trapped mineral matter from the tidal river may have otherwise been deposited on the marsh platform had the ditches not been in place.

Overall, the agreement between excess ²¹⁰Pb and ¹³⁷Cs-derived rates of accretion and accumulation was excellent; at most of the sites the rates differed by \leq 15%. This is a noteworthy observation considering that bioturbation and physiochemical processes have potential to mix or perturb radionuclide profiles (Sharma et al., 1987; Harvey et al., 2007). Another important observation is the presence of measurable ¹³⁷Cs activity at the tops of all of the cores. Given that the global atmospheric flux of ¹³⁷Cs has been negligible since the early 1980s (excluding regional events like the Chernobyl accident), these results suggest that previously deposited ¹³⁷Cs has been redistributed in the system. In general, additional ¹³⁷Cs can be supplied to a marsh by upland soil erosion in the watershed or through channel bed and bank erosion within the tidal segment of the estuary. Cores MK-1B and MK-2B show slight evidence for biological mixing in the top 10 cm (Figures 4 and 5), but the shapes of the radionuclide profiles for all ten cores are not indicative of intense biological mixing at depth.

3.5 Radionuclide Inventories and Focusing Factors

Radionuclide inventories and focusing factors for the ten coring sites are listed in Table 2 and presented graphically in Figures 29 and 30. Sediment inventories of excess ²¹⁰Pb and ¹³⁷Cs were computed to compare the relative amount of radionuclide preserved among the ten coring sites. Reference inventories of 28 dpm cm⁻² for excess ²¹⁰Pb and 21 dpm cm⁻² for ¹³⁷Cs are known from direct measurements of radionuclide atmospheric deposition in the U.S. Mid-Atlantic region (Olsen et al. 1985; Graustein and Turekian, 1986). These reference values represent the total

amount of radionuclide that could be buried at a site if supplied by atmospheric deposition alone.

Examining the movement of sediment from one depositional environment to another requires knowledge of how each radionuclide behaves differently in an estuarine environment. Tidal flooding can supply additional ²¹⁰Pb to a tidal marsh in addition to that derived by direct atmospheric deposition because coastal and estuarine waters contain large quantities of particle-bound and dissolved ²¹⁰Pb available for deposition (Church and Sarin, 1995; Velinsky, et al., 2010). Conversely, freshwater systems (i.e. lakes) accumulate only atmospherically derived (unsupported) ²¹⁰Pb (Robbins, 1978). For this reason, tidal marshes in saline or brackish waters have potential to accumulate more excess ²¹⁰Pb than tidal freshwater marshes. Similarly, salt marsh areas that rest low within the tidal frame and thus flood more frequently have potential to accumulate more excess ²¹⁰Pb than in the adjacent high marsh. ¹³⁷Cs behaves similarly to ²¹⁰Pb but is less particle-reactive and thus tends to desorb from fine-grained sediments in the presence of cations like potassium (Benninger and Wells, 1993). Consequently, depositional sites in predominantly freshwater environments should exhibit higher ¹³⁷Cs inventories than ones in saltwater environments. Hence, both physiochemical and sedimentary processes must be taken into account when interpreting radionuclide inventories for tidal marsh sediments. Insight can be gained into the relative influence of these processes on radionuclide burial by examining how measured radionuclide inventories vary with the initial activity of the radionuclide (A_o in Equation 6) and the sediment accumulation rate.

All sample locations had ²¹⁰Pb focusing factors >1 (Table 2, Figure 30). Whereas the non-ditched sites showed good agreement between ²¹⁰Pb focusing factors,

the inter-ditch marsh sites exhibit variability in terms of radionuclide focusing. Sites MK-5 and MK-9 had excess ²¹⁰Pb focusing factors similar to the non-ditched sites, suggesting that the ditched marsh at these sites does not sequester more radionuclide than a comparable non-ditched marsh. However, at site MK-7 the ²¹⁰Pb focusing factor is 3.36, which reveals that this site accumulates relatively more radionuclide by sediment focusing. Recalling that ditches appear to be preferential traps for mineral mud, it is no surprise that ditch sites MK-8 and MK-10 have the highest ²¹⁰Pb focusing factors of all cores (FF=4.83 for both). The ²¹⁰Pb focusing factor at site MK-6 (FF=2.3) is much less than the other focusing factors at ditch sites, reiterating that the processes of sediment and radionuclide deposition are not the same for all locations, though this may be a result of differences in ditch construction.

All sites had ¹³⁷Cs focusing factors <1 (Table 2, Figure 30). In this case, ¹³⁷Cs focusing factors for all ten sites are depleted evenly, confirming that the Murderkill River estuary is well-mixed along its axis and that dissolved substances and suspended matter entering the estuary at any point can be deposited virtually anywhere in the fringing marsh. Whereas ¹³⁷Cs inventory at all sites seems to be controlled by saltwater ions outcompeting fine sediment for sorption during flood tide, ²¹⁰Pb is not. If deposition of ²¹⁰Pb and ¹³⁷Cs were controlled by the same processes, the patterns in inventories would be the same for both radionuclides. While it is true that tides remove ¹³⁷Cs from the marsh equally, thus explaining the low ¹³⁷Cs inventories at all sites, the fact that tides bring extra ²¹⁰Pb to the marsh is not enough to explain the considerable variability in ²¹⁰Pb inventories. As shown in Figure 29, there is a statistically significant (P < 0.0001) positive correlation between ²¹⁰Pb inventory and mass accumulation rate, which suggests that spatial variations in

inventory are controlled to a greater extent by sediment accumulation and than by the amount of ²¹⁰Pb available for deposition. In other words, the type (mineral, organic) and supply of sediment are the limiting factors for ²¹⁰Pb inventory, not the initial activity of excess ²¹⁰Pb available in seawater. The two largest ²¹⁰Pb focusing factors come from ditch cores which have evidence of preferential infilling of mineral sediment, and the third-largest ²¹⁰Pb focusing factor correspond to MK-7 which showed an increase in mineral matter preservation upcore.

Chapter 4

DISCUSSION

4.1 Spatial Variations in Accretion and Mass Accumulation Rate

The accretion rates computed from the ten marsh cores range from 0.27 -1.24 cm yr⁻¹ with a mean of 0.61 ± 0.30 cm yr⁻¹ (1 σ , n=20). These rates fall within range of accretion rates computed from Delaware Bay salt marshes in studies by Stumpf (1983), in an non-ditched marsh in Lewes, Delaware; Kraft et al. (1992), 22 cores in 14 marshes along the Delaware coast including Bowers Beach, Delaware, near the confluence of the Murderkill River and Delaware Bay; Nikitina et al. (2000) from a synthesis of 28 cores along the Delaware coast of Delaware Bay; Church et al. (2006), from upper Delaware River estuary cores at two sites. Sommerfield and Velinsky (2010) report the range of excess ²¹⁰Pb accretion rates at sites spanning tidal freshwater marsh to salt marshes to be 0.3-1.3 cm yr⁻¹ with a mean of 0.50 ± 0.4 cm vr^{-1} (1 σ , n=32 cores). The marshes mentioned by Sommerfield and Velinsky (2010) cover a large geographic area and include freshwater and brackish water marshes, upper/lower Delaware Bay, and modified/unmodified marshes. The rate of sea level rise recorded at Lewes, Delaware over the past 90 years is $0.32 \text{ cm yr}^{-1} \pm 0.028 \text{ cm yr}^{-1}$ (NOAA, 2008). The lowest accretion rates are from sites MK-4, MK-5 and MK-9 although they are of similar magnitude as the rate of sea level rise. While the local rate of sea level rise in the Murderkill River may be different than Lewes because of differences in rates of subsidence or sediment compaction, most sites within the

Murderkill River estuary will not be flooded if sea level continues to rise at current rates.

The mosquito ditches themselves accrete at rates in excess of sea level rise because they fall relatively low within the tidal frame and are flooded more frequently than the adjacent marsh platform. This allows relatively more suspended sediment to be transported from the Murderkill River to the ditch. In a study of marsh accretion in Port Mahon, Delaware, Khaleguzzaman, (1989) found evidence that sediment accretion rates on marsh platforms increased by 0.1 cm yr^{-1} after ditching was completed. The higher accretion rates were attributed to increased sediment availability to the marsh surface due to the placement of ditch spoils directly on the marsh surface. Similarly, a review of historical records confirms that ditch spoils were placed directly on the marsh surface in the Murderkill during the 1930s ditching work, and during 1963 ditching activities (Corkran, 1937; DELDOT, 1963). In contrast, in marshes of the Murderkill River there does not appear to be a sudden change in sediment accumulation rate at the inter-ditch sites that could be linked to the presence of ditches. Thus, the hypothesis that ditches enhance sediment accumulation on the vegetated marsh platform is not supported by the results of this study. This appears to be related to the fact that the ditches provide a topographic trap for suspended sediments. Since depositional processes can vary greatly even over short distances, little can be said about deposition far into the marsh interior (> 100 m from riverbank), since all cores were collected within 70 m of the tidal river.

4.2 Historical Sediment Change in MK-1B and MK-2B

The results of this study demonstrate that the Murderkill River estuary is a well-mixed, mineral-dominated salt marsh where the nature of sediment accumulation has for the most part not changed appreciably during the past century. However, there are exceptions to this overall pattern. Beginning at approximately 50 cm depth in cores MK-1B and MK-2B, there is an abrupt change in sediment properties (Figure 4 and Figure 5). Upcore, the sediment color becomes lighter, the texture changes from muddy peat to peaty mud, the consistency shifts from firm to soft, the water content increases, LOI values decrease significantly, and fine silt and clay mass percentages increase at the expense of sortable silt (Figures 15 and 16). Radionuclide dating placed this change at the late 1940s to mid 1950s. One possibility is that this shift was related to the construction of US Route 113 bypass of the town of Frederica; however, the bypass was constructed in 1964-1965, which postdates the changes present in cores MK-1B and MK-2B, thus removing it as a potential cause. Despite occurring at nearly the same time as the first round of mosquito ditching, the distance separating sites MK-1 and MK-2 with ditched areas was considered too great to be directly responsible for this shift upriver.

Velinsky et al. (2010) analyzed the sediment at MK-1 and MK-2 for changes in stable isotopes of carbon and diatom assemblages. They showed that the darker, deeper sediment contained stable isotope concentrations and diatom assemblages indicative of a freshwater setting overlain by sediment with stable isotope concentrations and diatoms indicative of a brackish setting. Therefore, the sediment cores at MK-1 and MK-2 captured the shift from a freshwater to brackish setting which seems to have occurred in the 1940s to 1950s, though the cause is unknown. Dredging in the upper river could be responsible, since dredging allows for farther

landwards penetration of brackish waters (Kennish, 2001). However, there is no written record of dredging activities in the Murderkill River, though the town of Frederica was formerly a site of commercial shipping and fishing so there may have been a need (University of Delaware, 2004). Further investigation into the types of land-use and waterway management practices in effect in the early 1900s is needed to decipher the ecological changes documented in cores MK-1B and MK-2B.

4.3 Influence of Mosquito Ditches on Tidal Marsh Sediment Accumulation

Measurable ¹³⁷Cs in ditch cores at the maximum depth of ditching signifies that the older sediment lacking ¹³⁷Cs excavated from the ditch is not the dominant constituent which infilled the ditches after it was removed in 1963. Ditches may have filled with a mix of ditch spoil and new sediment, thus creating the series of sediment intervals with low but detectable ¹³⁷Cs activities, but based on evidence from ¹³⁷Cs inventories it appears more likely that ditches infilled with only new material. Since being cleaned in 1963, ditch stratigraphy is missing the first 9 years of ¹³⁷Cs deposition (1954-1963), yet two of the three ditch cores have inventories similar to non-ditch cores which recorded the entire history of this radionuclide (Figure 30). The most likely way for ditches to have comparable ¹³⁷Cs inventories is for them to rapidly accrete sediment when ¹³⁷Cs was readily available during the 1960s and shortly thereafter instead of with a mix of old and new sediment. ¹³⁷Cs entering the estuary from anywhere could be transported to and deposited anywhere or preferentially deposited in ditches. In this way, ditches would be able to match the

¹³⁷Cs inventory of non-ditched sites without the first 9 years of ¹³⁷Cs depositional history.

Trends in ²¹⁰Pb activities for sediment at the bottom of ditches support this hypothesis, but there is a caveat to this interpretation. Once it was dispersed onto the marsh platform, ditch spoil sediments may have sorbed additional ¹³⁷Cs and ²¹⁰Pb once exposed to the atmosphere and tides, then returned to the ditch and appear to be new sediment. However, this process could only have happened for the few tidal cycles immediately after ditching activities were complete since the tides would homogenize the ditch spoil with the suspended river sediment and all radionuclide signatures of ditch spoil would be lost. Even if all the spoil sediment acquired new radionuclides and returned to the ditch, the sediment in the ditch would be unconsolidated and tidal energy would remove much of it to the tidal river. At most ~5 cm of sediment at the bottom of ditches could be new sediment. Using the methods in this study it is impossible to determine if the sediment at the bottom of ditches is new sediment or ditch spoil with freshly-acquired radionuclides.

Khalequzzaman (1989) determined that sedimentation rates on the marsh platform increased after ditching activity because ditch spoils were dumped in the inter-ditch parts of the marsh, providing a local source of material for redeposition on the marsh platform. If the spoils were preserved on the marsh surface in the Murderkill, inter-ditch cores should have some physical record of it either in the form of increased dry bulk density, decreased LOI or increased mineral volume composition. However, none of the inter-ditch cores show evidence of a pulse of mineral matter (Figures 8 and 19 for MK-5B; Figures 10 and 21 for MK-7B; Figures

12 and 23 for MK-9B) as would be expected if the ditch spoils were retained on the marsh platform (e.g., Khalequzzaman, 1989).

Assuming ditch geometry matches the descriptions in historical records (50.8 cm deep, 25.4 cm wide, variable length), a simple calculation can be used to determine the thickness of a spoil layer if it was entirely preserved on the marsh platform. Based on photographic evidence, spoils were distributed to a distance ~3 to 5 m from the ditch bank (Corkran, 1937; DELDOT, 1963). Therefore, given a section of marsh platform 100 cm long along the ditch edge and extending 300 to 500 cm away from the ditch, the spoil layer would be between 2.15 and 1.29 cm thick (Figure 31). If the entire inter-ditch area (~ 20 m away from ditch edge) was evenly covered, the spoil layer would be ~ 0.28 cm thick, which would be nearly impossible to differentiate from sediment brought in from the tidal river. Ditch cores were collected in the center of inter-ditch areas, therefore the only way ditch spoil would be preserved in these cores was for it to be transported to the center of the inter-ditch ~ 20 m from both adjacent ditches. Considering that sedimentological tests were performed on every other 2-cm section of extruded sediment, it is possible that a spoil layer may be preserved in an un-tested interval of sediment. However, these findings suggest that excavated ditch mud is neither chemically or sedimentologically unique enough to be differentiated from recent, non-spoil marsh sediment, or that ditch spoil was not preserved on the marsh surface in significant quantities as it would only be evident as a thin veneer in the sediment column.

Unquestionably, ditches trapped sediment quickly after construction as evidenced by the downcore radionuclide profiles for ditch cores, and near-surface activities of ²¹⁰Pb prove that the ditches are currently depositional (Figures 9, 11, and

13). Now that many ditches have infilled partially, the following hypothetical example may describe the relationship between mostly-filled ditches like in the Murderkill, and the inter-ditch marsh platform: floodwater enters the ditch prior to breaching the riverbank where minor accumulation takes place. Upon breaching the ditch, suspended sediment is transported to and deposited on the marsh platform, where slack tide allows deposition on the platform and in the ditch. Thorough drainage at ebb tide due to ditches (LeMay, 2007) returns water to the ditch, bringing with it all un-deposited sediment on the platform. Ebb tide exits through the ditch, but the ditch may remain inundated even at low tide, allowing further deposition to occur there. In this hypothetical example, the ditch acts as preferred tidal pathway into and out of the marsh, and allows sediment transport to occur on the marsh platform before the riverbank is breached. However, the ditch performs its function and drains the marsh too thoroughly for enhanced deposition to occur on the platform despite increasing the hydroperiod. In this example ditches themselves cannot accrete as quickly as they did when they were first constructed because tidal action is preventing enhanced accumulation from happening even though flow velocities in ditches were observed to be small during flood (W. Ullman, personal communication). This example is concordant with observations in the field regarding flood tide propagating into the ditched area of the Murderkill River estuary and radionuclide data from the tops of ditch cores. This is also corroborated by hydrodynamic observations made by LeMay (2007) who observed that inter-ditch areas stay inundated longer than nonditched areas and that ditched areas drain more evenly and thoroughly than nonditched areas. In this example, the marsh platforms in ditched areas still accumulate

sediment to maintain elevation against sea level rise, but not at rates in excess of local sea level rise, as hypothesized by this study.

As it is, the ditches remain low-elevation features on the marsh which have developed small berms colonized by dense vegetation and have yet to in-fill completely (Figure 32). It is possible that ditches are approaching an equilibrium elevation with respect to the marsh platform, and the relationship between a ditch at equilibrium may be different from a ditch still infilling. Consider the volumetric composition profiles for inter-ditch cores MK-5B, MK-7B and MK-9B: MK-7B shows an increase in mineral matter beginning shortly after ditching in the 1930s (Figure 21), and MK-5B and MK-9B show decreases in mineral matter after the 1930s followed by what could be the start of a mineral increase to the present (Figures 19 and 23). These cores may record the progression of mineral accumulation effects on the platform as nearby ditches approach equilibrium elevation: starvation, as ditches act as preferential sinks for mineral sediment (decreased mineral volume), followed by enhancement when ditches reach equilibrium (increased mineral volume). If this is true, MK-7B and its nearby ditches appear to be operating under the equilibrium scenario for some time, while MK-5B and MK-9B are approaching it. However, it is impossible to definitively attribute this change in mineral composition to ditching based on methods used in this study.

It is interesting to note that, with the exception of sites MK-1B and MK-2B, there is no statistical difference in the grain-size properties of the marsh sediment column sampled in this study. All cores have overlapping median grain size distributions and highly continuous grain size distributions downcore, which can be interpreted to mean that human impacts in the Murderkill River estuary have not

significantly affected the hydraulic sorting of muddy sediments delivered to the marsh (Figure 26). Ditch and inter-ditch grain-size distributions shown in Figures 26 and 27 demonstrate how little variation there is between the two depositional environments.

Despite the geographical proximity of some core sites it is clear that sedimentary processes acting on the marsh platform can vary significantly even over short distances. Based on the methods used in this study it appears that mosquito ditches have had little to no effect on sediment bulk properties and accumulation on the marsh platform which can be attributed exclusively to ditches since their construction in the mid 1930s.

Chapter 5

CONCLUSIONS

The sedimentological and radionuclide properties of sediment cores collected in tidal marshes of the Murderkill River estuary reveal it to be a well-mixed estuary where vertical accretion and mass accumulation are dominated by mineral matter. An overarching conclusion of this study is that all ten of the marsh sites investigated are depositional and under the influence of both local and basin-wide processes that influence sediment and radionuclide delivery to the marsh platform. Sediment accretion rates derived from ²¹⁰Pb and ¹³⁷Cs measurements from the Murderkill river estuary are similar to rates computed from other marshes within the Delaware Estuary and range from 0.27 to 0.72 cm yr⁻¹ with corresponding mass accumulation rates between 0.10 and 0.18 g cm⁻² yr⁻¹. Accretion and mass accumulation rates from ditches are 0.50 to 1.24 cm yr⁻¹ and 0.25 to 0.55 g cm⁻² yr⁻¹. There was good agreement between the ¹³⁷Cs rates and ²¹⁰Pb using the Constant Initial Concentration ²¹⁰Pb model, suggesting there has been little post-depositional mixing of the sediment column. Organic accumulation in the marsh has remained constant throughout most of the estuary over the past century as evidenced by near-constant organic contribution to sediment volume over time.

Median grain size and sorting through the study area appear to be unaffected by the presence of mosquito ditches, as cores from ditched and non-ditched areas alike had similar median and sorting distributions. Profiles of excess ²¹⁰Pb and ¹³⁷Cs activity suggest that the mosquito ditches began to fill quickly with mineral sediment after construction. However, ditches have not filled in completely and remain low elevation features on the marsh, perhaps being kept open by tidal action as they approach some equilibrium elevation with respect to the adjacent marsh platform. Inter-ditch sites in the ditched area of the marsh have similar vertical accretion rates to the non-ditched marsh sites, suggesting that sediment accumulation within the ditches does not appear to augment delivery of sediment to the marsh as hypothesized at the outset of this study. Ditches appear to have little to no effect on mineral sediment accumulation rates in the inter-ditch marsh and there is no evidence to suggest ditches have deprived the marsh platform of suspended sediment in order to infill. Also, the presence of ditches does not appear to influence marsh sedimentation in non-ditched marshes of the estuary.

Future Work

More work is needed to understand the consequences of mosquito ditching in salt marshes of the Delaware Estuary and along the U.S. Atlantic coast as a whole. Cores MK-1B, MK-3B and MK-7B could have been analyzed deeper for radionuclides to ensure samples deposited during both the mosquito ditching programs were included. Future studies attempting to answer the question of short-term deposition and whether or not accumulation rates are decreasing in ditches, the shortlived radionuclide ⁷Be (half-life 53.3 days) could be used. In terms of sedimentation, understanding if both ditches bordering an inter-ditch section of marsh behave in the same manner could prove useful. Future work on the effects of anthropogenic activities on marsh sedimentation should consider measuring stem density between sites, as greater stem density yields larger accretion rates. A downcore ecological

investigation of inter-ditch cores to determine what effect ditches had on changing the dominant plant species on the marsh, which may influence ability for marsh to accrete sediment, could be informative. If trying to investigate changes in accretion over time, using the CRS model to acquire multiple accretion rates per core could prove useful. If attempting to draw parallels between elevation and accumulation, on-site GPS elevation data would prove more useful than LIDAR elevations, which can be confused by marsh vegetation canopy. Lastly, collecting a transect of several cores in a ditch moving away from the river channel could be helpful in determining if accumulation or grain size correlate to distance from the river channel in the ditch, similar to the way the conceptual model of marsh accumulation works once flood tide breaches the riverbank.

TABLES & FIGURES

Location	Core Name	Date	Lat (N)	Lon (W)	Depth of Core (cm)	NAVD88 Elevation (m)
1km downriver of Rt. 1	MK-1A	10-Oct-08	39° 00.587'	75° 26.963'	73.8	0.60
	MK-1B	10-Oct-08	39° 00.584'	75° 26.962'	82	0.81
1.3km downriver of Rt. 1	MK-2A	10-Oct-08	39° 00.662'	75° 26.390'	91	0.61
	MK-2B	10-Oct-08	39° 00.662'	75° 26.391'	94	0.61
Mid River	MK-3A	10-Oct-08	39° 01.556'	75° 24.751'	98.5	0.64
	MK-3B	10-Oct-08	39° 01.555'	75° 24.750'	98	0.62
Near USGS Gage on S. Bowers Rd	MK-4A	10-Oct-08	39° 02.997'	75° 23.523'	104	0.91
	MK-4B	10-Oct-08	39° 02.998'	75° 23.521'	96	0.96
~1km west of MK-4 in ditched area of marsh	MK-5A	22-Oct-09	39° 02.890'	75° 24.211'	72	0.73
	MK-5B	22-Oct-09	39° 02.890'	75° 24.211'	68	0.73
	MK-6A	22-Oct-09	39° 02.891'	75° 24.222'	80	0.53*
	MK-6B	22-Oct-09	39° 02.891'	75° 24.222'	80	0.53*
	MK-7A	22-Oct-09	39° 02.993'	75° 24.283'	108	0.68
	MK-7B	22-Oct-09	39° 02.993'	75° 24.283'	100	0.68
	MK-8A	22-Oct-09	39° 02.938'	75° 24.301'	86	0.48*
	MK-8B	22-Oct-09	39° 02.938'	75° 24.301'	90	0.48*
	MK-9A	22-Oct-09	39° 02.751'	75° 24.052'	107	0.63
	MK-9B	22-Oct-09	39° 02.751'	75° 24.052'	80	0.63
	MK-10A	22-Oct-09	39° 02.763'	75° 24.066'	82	0.43*
	MK-10B	22-Oct-09	39° 02.763'	75° 24.066'	88	0.43*

Table 1Sediment core locations and collection dates.

*Elevations for ditch cores at MK-6, MK-8 and MK-10 are estimated.

Site	¹³⁷ Cs 1963 accretion (cm/y)	1963 Bulk MAR (g/cm²/y)	¹³⁷ Cs inventory (dpm/cm ²)	CIC ²¹⁰ Pb accretion (cm/y)	CIC ²¹⁰ Pb Bulk MAR (g/cm ² /y)	Excess ²¹⁰ Pb inventory (dpm/cm ²)	Excess ²¹⁰ Pb Focus Factor	¹³⁷ Cs Focus Factor
MK1B	0.67	0.20	9.40	0.72	0.19	64.17	2.29	0.45
MK2B	0.67	0.11	10.25	0.72	0.13	46.87	1.67	0.49
MK3B	0.40	0.10	10.26	0.57	0.13	42.75	1.53	0.49
MK4B	0.29	0.14	8.99	0.33	0.14	50.03	1.79	0.43
MK5B	0.37	0.15	7.25	0.32	0.12	69.77	2.49	0.35
MK6B	0.63	0.32	3.00	0.50	0.25	64.34	2.30	0.14
MK7B	0.54	0.25	8.81	0.48	0.17	94.02	3.36	0.42
MK8B	1.15	0.49	5.86	1.05	0.44	135.12	4.83	0.28
MK9B	0.28	0.11	7.63	0.27	0.10	50.73	1.81	0.36
MK10B	1.24	0.61	9.73	1.04	0.51	135.13	4.83	0.46

Table 2Accretion and mass accumulation rates, radionuclide inventories and
focusing factors.



Figure 1 Conceptual model of processes affecting salt marsh accretion and elevation change. From French (2006).



Figure 2 Map of the study area showing the Murderkill river watershed with tidally-influenced portions of the river in bold. Sediment coring locations are located within the red square. Modified from Wong et al. (2009).



Figure 3 Study area detail. The top panel shows the locations of cores MK-1 through MK-4. The bottom panel is an aerial photograph showing coring locations MK-5 through MK-10 in the heavily ditched area.



Figure 4Sediment properties and radionuclide profiles for core MK-1B.
"LOI" is loss-on-ignition and "DBD" is dry bulk density. In this
and subsequent radionuclide profiles, the blue arrow signifies the
onset of ¹³⁷Cs deposition, and the red arrow is peak ¹³⁷Cs deposition.



Figure 5 Sediment properties and radionuclide profiles for core MK-2B.



Figure 6 Sediment properties and radionuclide profiles for core MK-3B.



Figure 7 Sediment properties and radionuclide profiles for core MK-4B.



Figure 8 Sediment properties and radionuclide profiles for core MK-5B.



Figure 9 Sediment properties and radionuclide profiles for ditch core MK-6B.


Figure 10 Sediment properties and radionuclide profiles for core MK-7B.



Figure 11 Sediment properties and radionuclide profiles for ditch core MK-8B.



Figure 12 Sediment properties and radionuclide profiles for core MK-9B.



Figure 13 Sediment properties and radionuclide profiles for ditch core MK-10B.



Figure 14 Correlation between dry bulk density (DBD) and loss-on-ignition (LOI) for all cores.



Figure 15 Volumetric composition and grain-size profiles for core MK-1B. In this and subsequent volume composition plots, the red line signifies the depth at which excess ²¹⁰Pb reaches zero or is below detectable limits, and dates below this line are linearly extrapolated.



Figure 16 Volumetric composition and grain-size profiles for core MK-2B.



Figure 17 Volumetric composition and grain-size profiles for core MK-3B.



Figure 18 Volumetric composition and grain-size profiles for core MK-4B.



Figure 19 Volumetric composition and grain-size profiles for core MK-5B.



Figure 20 Volumetric composition and grain-size profiles for ditch core MK-6B.



Figure 21 Volumetric composition and grain-size profiles for core MK-7B.



Figure 22 Volumetric composition and grain-size profiles for ditch core MK-8B.



Figure 23 Volumetric composition and grain-size profiles for core MK-9B.



Figure 24 Volumetric composition and grain-size profiles for ditch core MK-10B.



Figure 25 Ternary diagrams for cores from non-ditched areas of the marsh.



Figure 26 Ternary diagrams for all depth intervals in all cores.



Figure 27 A) Scatter plot of median grain diameter versus sorting for the mud fraction of subsamples from cores MK-1B, 2B, 3B, and 4B and ditch cores. B) Scatter plot of cores MK-1B, 2B, 3B, and 4B and the interditch cores.



Figure 28 LOI versus grain size mass percentages. Mass percentages of panels B, C and D are based on the mud fraction only.



Figure 29 Scatter plot of ²¹⁰Pb inventory versus ²¹⁰Pb-derived mass accumulation rate (MAR) for all ten cores.



Figure 30 Focusing factors of ¹³⁷Cs and ²¹⁰Pb for all cores collected in this study. A focusing factor of two suggests that the depositional site has sequestered two times the reference inventory of the radionuclide in question. See text for discussion.





Figure 31 Diagram showing placement of ditch spoil on marsh platform. The thickness of the spoil layer in the bottom panel is dependent on the distance the layer extends away from the ditch. See text for discussion. Figure not to scale.



Figure 32 Diagram of ditch progression: (A) undisturbed marsh platform; (B) ditch construction; (C) ditch infilling; (D) present day. See text for discussion.

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APPENDIX A

Appendix A contains radionuclide data as directly measured from the samples used in radionuclide plots (Figures 4-13).

Sample	Interval	Mass	Total 210 Pb	Excess 210 Pb	+/-	214 Bi (dnm/g)	+/-	137 Cs (dnm/g)	+/-
ID	(em)	(8)	(upin/g)	(upin/g)		(upin/g)		(upin 6)	
MK1B	0-4	23.8	8.33	7.71	0.65	0.62	0.06	0.46	0.03
MK1B	4-8	22.76	7.58	6.85	0.62	0.73	0.07	0.43	0.03
MK1B	8-12	26.58	8.38	7.54	0.65	0.85	0.08	0.37	0.03
MK1B	12-14	26.68	7.49	6.55	0.60	0.94	0.09	0.42	0.03
MK1B	14-16	16.55	8.19	6.82	0.70	1.37	0.12	0.52	0.04
MK1B	16-20	25.1	6.91	5.85	0.57	1.06	0.09	0.54	0.04
MK1B	20-24	23.99	5.23	4.09	0.47	1.14	0.10	1.34	0.07
MK1B	24-28	18.65	4.30	3.33	0.42	0.97	0.09	1.73	0.10
MK1B	28-32	24.6	4.16	3.32	0.40	0.83	0.08	2.27	0.11
MK1B	32-36	26.69	3.05	2.10	0.31	0.95	0.09	0.84	0.05
MK1B	36-40	21.05	2.15	1.20	0.25	0.95	0.09	0.25	0.02
MK1B	40-44	23.75	2.30	1.29	0.25	1.01	0.09	0.10	0.01
MK1B	44-48	15.34	2.68	2.00	0.31	0.68	0.07	0.05	0.00
MK1B	48-52	10.35	1.30	0.60	0.18	0.70	0.07	-0.04	0.00
MK1B	52-56	15.14	1.24	1.00	0.16	0.24	0.03	0.06	0.00
MK1B	56-60	13.02	0.86	0.62	0.13	0.23	0.03	-0.08	-0.01

Sample ID	Interval (cm)	Mass (g)	Total ²¹⁰ Pb (dpm/g)	Excess ²¹⁰ Pb (dpm/g)	+/-	²¹⁴ Bi (dpm/g)	+/-	¹³⁷ Cs (dpm/g)	+/-
MK2B	0-4	5.06	10.91	10.56	0.79	0.35	0.03	0.09	0.01
MK2B	4-8	11.37	11.68	11.13	0.67	0.55	0.04	0.11	0.01
MK2B	8-12	12.57	8.97	8.87	0.54	0.10	0.01	0.26	0.02
MK2B	12-16	8.82	8.57	8.27	0.57	0.29	0.03	0.01	0.00
MK2B	16-20	7.1	6.49	6.79	0.50	-0.30	-0.02	0.40	0.02
MK2B	20-24	8.61	6.11	5.74	0.46	0.38	0.03	0.58	0.03
MK2B	24-28	17.84	4.63	3.90	0.32	0.73	0.04	1.78	0.07
MK2B	28-32	22.8	3.91	3.22	0.27	0.69	0.04	4.43	0.13
MK2B	32-36	23.83	2.54	1.97	0.21	0.57	0.03	2.08	0.07
MK2B	36-40	27.78	2.60	1.89	0.20	0.71	0.04	0.70	0.03
MK2B	40-44	26.25	2.40	1.61	0.19	0.79	0.04	0.32	0.02
MK2B	44-48	14.75	1.52	1.02	0.15	0.51	0.03	0.11	0.01
MK2B	48-52	11	0.84	1.04	0.09	-0.20	-0.01	-0.10	-0.01
MK2B	52-56	10.44	0.71	0.36	0.11	0.35	0.02	0.23	0.01
MK2B	56-60	15.01	0.53	-0.06	0.08	0.60	0.04	-0.04	-0.01
MK2B	60-64	14.11	0.65	0.73	0.09	-0.08	-0.01	-0.08	0.00
MK2B	64-68	15.61	-0.05	-0.13	-0.01	0.08	0.01	0.01	0.00
MK2B	68-72	11.12	1.04	1.24	0.13	-0.20	-0.01	-0.10	-0.01
MK2B	72-76	8.67	-0.07	-0.38	-0.17	0.31	0.02	0.01	0.00
MK2B	76-80	10.09	0.88	0.14	0.13	0.74	0.05	-0.10	-0.01
MK2B	80-84	12.51	0.62	0.68	0.10	-0.06	-0.01	-0.07	-0.02
MK2B	84-88	13.22	0.55	0.43	0.09	0.12	0.01	0.06	0.00
MK2B	88-92	19.7	0.77	0.41	0.10	0.36	0.03	0.02	0.00
MK2B	92-94	10.81	0.07	-0.24	0.03	0.31	0.02	0.16	0.01

Sample ID	Interval (cm)	Mass (g)	Total ²¹⁰ Pb (dpm/g)	Excess ²¹⁰ Pb (dpm/g)	+/-	²¹⁴ Bi (dpm/g)	+/-	¹³⁷ Cs (dpm/g)	+/-
MK3B	0-4	21.86	11.85	11.44	0.85	0.42	0.04	0.29	0.02
MK3B	4-6	14.07	8.67	7.51	0.75	1.16	0.11	0.23	0.02
MK3B	6-8	16.55	7.11	6.73	0.63	0.38	0.04	0.46	0.03
MK3B	8-12	17.66	6.18	5.62	0.56	0.56	0.06	1.12	0.07
MK3B	12-16	24.11	6.33	5.75	0.53	0.58	0.06	3.61	0.16
MK3B	16-20	15.69	4.22	3.74	0.43	0.48	0.05	4.70	0.21
MK3B	20-24	13.49	4.27	4.24	0.44	0.03	0.00	2.04	0.12
MK3B	24-28	12.51	3.92	3.44	0.42	0.47	0.05	0.21	0.02
MK3B	28-32	22.22	2.44	1.68	0.27	0.75	0.07	0.21	0.02
MK3B	32-36	20.72	2.40	1.43	0.27	0.97	0.09	0.08	0.01
MK3B	36-40	16.85	1.36	0.72	0.18	0.64	0.07	-0.12	-0.01
MK3B	40-44	13.51	1.23	1.03	0.17	0.20	0.02	-0.14	-0.01
MK3B	44-48	25.07	1.13	0.58	0.15	0.56	0.06	-0.04	-0.01
MK3B	48-52	24.76	1.60	0.77	0.20	0.84	0.08	-0.08	-0.01

Sample ID	Interval (cm)	Mass (g)	Total ²¹⁰ Pb (dpm/g)	Excess ²¹⁰ Pb (dpm/g)	+/-	²¹⁴ Bi (dpm/g)	+/-	¹³⁷ Cs (dpm/g)	+/-
MK4B	0-2	29.89	9.93	8.84	0.49	1.08	0.05	0.32	0.02
MK4B	2-4	22.42	10.08	9.02	0.52	1.06	0.06	0.17	0.01
MK4B	4-6	27.42	8.46	7.39	0.44	1.07	0.06	0.28	0.02
MK4B	6-8	30.22	6.25	5.45	0.36	0.81	0.04	0.85	0.04
MK4B	8-12	26.31	4.97	4.28	0.31	0.69	0.04	2.00	0.07
MK4B	12-14	25.36	3.79	3.04	0.26	0.75	0.04	2.06	0.07
MK4B	14-16	20.54	4.03	3.21	0.28	0.82	0.05	1.80	0.07
MK4B	16-20	26.38	2.89	2.12	0.22	0.77	0.04	0.63	0.03
MK4B	20-22	31.21	2.27	1.17	0.18	1.10	0.06	0.24	0.01
MK4B	22-24	19.18	2.10	1.18	0.19	0.91	0.05	0.00	0.00
MK4B	24-26	19.8	1.92	0.66	0.18	1.26	0.07	0.01	0.00
MK4B	26-28	27.24	1.91	0.77	0.16	1.15	0.06	0.00	0.00
MK4B	28-30	29.74	1.46	0.43	0.14	1.03	0.05	-0.02	0.00
MK4B	30-32	29.45	2.24	1.22	0.18	1.01	0.05	0.04	0.00
MK4B	32-34	37.72	1.49	0.17	0.14	1.32	0.06	0.01	0.00
MK4B	34-36	33.44	1.31	0.31	0.14	1.00	0.05	-0.04	0.00
MK4B	36-38	39.95	1.13	-0.23	0.12	1.36	0.06	0.03	0.00
MK4B	38-40	33.99	1.77	0.76	0.15	1.01	0.05	-0.04	0.00
MK4B	40-42	36.03	1.22	0.05	0.13	1.17	0.06	0.11	0.01
MK4B	42-44	36.96	1.28	-0.10	0.13	1.39	0.07	-0.04	0.00
MK4B	44-46	35.47	0.63	-0.51	0.08	1.14	0.06	-0.04	0.00
MK4B	46-48	34.98	1.76	0.44	0.15	1.31	0.06	0.03	0.00
MK4B	48-50	34.91	1.70	0.36	0.15	1.34	0.06	-0.03	-0.01

Sample ID	Interval (cm)	Mass (g)	Total ²¹⁰ Pb (dpm/g)	Excess ²¹⁰ Pb (dpm/g)	+/-	²¹⁴ Bi (dpm/g)	+/-	¹³⁷ Cs (dpm/g)	+/-
MK5B	0-2	32.54	11.45	10.73	0.52	0.71	0.04	0.30	0.02
MK5B	4-6	32.01	9.34	8.47	0.47	0.87	0.05	0.31	0.02
MK5B	8-10	33.15	6.52	5.42	0.36	1.10	0.05	0.58	0.03
MK5B	12-14	33.7	7.19	6.11	0.39	1.09	0.05	0.62	0.03
MK5B	16-18	33.61	6.15	5.26	0.35	0.89	0.05	1.39	0.05
MK5B	20-22	28.18	4.25	3.32	0.28	0.94	0.05	0.78	0.04
MK5B	24-26	33.45	3.88	2.93	0.26	0.95	0.05	0.59	0.03
MK5B	28-30	33.06	1.60	0.66	0.12	0.94	0.05	0.18	0.01
MK5B	32-34	36.49	1.72	0.62	0.17	1.10	0.05	0.06	0.01
MK5B	36-38	35.55	1.80	0.75	0.16	1.05	0.05	0.01	0.00
MK5B	40-42	36.96	1.43	0.19	0.14	1.23	0.06	0.13	0.01
MK5B	44-46	39.42	0.93	-0.03	0.11	0.96	0.05	0.06	0.00
MK5B	48-50	37	1.11	0.35	0.12	0.76	0.04	-0.04	0.00
MK5B	52-54	31.7	1.96	0.82	0.17	1.14	0.06	-0.01	0.00
MK5B	56-58	36.87	1.59	1.18	0.13	0.41	0.04	-0.04	0.00
MK5B	60-62	38.08	1.21	0.31	0.12	0.90	0.05	-0.04	0.00
MK5B	64-66	34.34	1.49	0.38	0.14	1.11	0.06	-0.04	0.00

Sample ID	Interval (cm)	Mass (g)	Total ²¹⁰ Pb (dpm/g)	Excess ²¹⁰ Pb (dpm/g)	+/-	²¹⁴ Bi (dpm/g)	+/-	¹³⁷ Cs (dpm/g)	+/-
MK6B	0-2	37.36	9.79	8.25	0.69	1.54	0.12	0.13	0.01
MK6B	4-6	36.63	10.69	9.09	0.73	1.60	0.12	0.25	0.02
MK6B	8-10	32.52	7.03	5.39	0.56	1.65	0.13	0.26	0.02
MK6B	12-14	37	4.70	3.24	0.42	1.46	0.12	0.29	0.02
MK6B	16-18	38.12	3.89	2.23	0.36	1.66	0.13	0.34	0.02
MK6B	20-22	35.93	3.68	2.26	0.35	1.42	0.11	0.22	0.02
MK6B	24-26	36.28	1.89	0.40	0.22	1.49	0.12	0.01	0.00
MK6B	28-30	39.95	2.06	0.65	0.23	1.41	0.11	0.04	0.00
MK6B	32-34	34.05	1.87	0.30	0.21	1.57	0.13	-0.03	0.00
MK6B	36-38	32.66	1.75	0.25	0.20	1.50	0.12	-0.02	0.00
MK6B	40-42	34.4	2.22	1.31	0.24	0.91	0.08	-0.07	-0.01
MK6B	44-46	34.9	0.80	-0.57	0.12	1.38	0.11	-0.07	-0.01
MK6B	48-50	33.12	1.06	-0.53	0.14	1.59	0.13	-0.07	-0.01
MK6B	52-54	33.02	1.88	0.65	0.21	1.22	0.10	-0.07	-0.01
MK6B	56-58	35.77	1.77	0.31	0.20	1.47	0.12	-0.06	-0.01
MK6B	60-62	32.57	1.08	-0.24	0.15	1.32	0.11	-0.07	-0.01
MK6B	64-66	34.22	1.43	0.00	0.17	1.43	0.12	-0.07	-0.01
MK6B	68-70	33.55	1.68	0.44	0.20	1.23	0.10	-0.07	-0.01
MK6B	72-74	31.72	1.13	-0.06	0.15	1.19	0.10	-0.07	-0.01
MK6B	76-78	31.98	1.69	0.31	0.20	1.38	0.11	-0.07	-0.01
Sample ID	Interval (cm)	Mass (g)	Total ²¹⁰ Pb (dpm/g)	Excess ²¹⁰ Pb (dpm/g)	+/-	²¹⁴ Bi (dpm/g)	+/-	¹³⁷ Cs (dpm/g)	+/-
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MK7B	0-2	33.02	13.40	12.38	0.86	1.02	0.09	0.12	0.01
MK7B	4-6	31.9	10.61	9.52	0.74	1.10	0.09	0.19	0.01
MK7B	8-10	34.85	7.49	6.21	0.58	1.28	0.11	0.14	0.01
MK7B	12-14	30.9	7.71	6.71	0.60	1.00	0.09	0.29	0.02
MK7B	16-18	31.18	6.53	5.49	0.53	1.04	0.09	0.44	0.03
MK7B	20-22	34.27	5.28	4.11	0.46	1.17	0.10	0.77	0.05
MK7B	24-26	35.41	4.98	3.77	0.44	1.21	0.10	2.14	0.10
MK7B	28-30	31.85	5.41	4.32	0.46	1.08	0.09	1.51	0.08
MK7B	32-34	31.01	4.05	3.02	0.38	1.03	0.09	0.26	0.02
MK7B	36-38	26.57	2.07	1.40	0.23	0.68	0.07	0.01	0.00
MK7B	40-42	24.62	1.36	0.46	0.16	0.89	0.08	-0.02	0.00
MK7B	44-46	24.31	0.80	-0.29	0.12	1.09	0.10	-0.02	0.00
MK7B	48-50	27.26	2.12	1.22	0.23	0.89	0.08	-0.08	-0.01
MK7B	52-54	23.43	1.10	0.41	0.15	0.69	0.07	-0.09	-0.01

Sample ID	Interval (cm)	Mass (g)	Total ²¹⁰ Pb (dpm/g)	Excess ²¹⁰ Pb (dpm/g)	+/-	²¹⁴ Bi (dpm/g)	+/-	¹³⁷ Cs (dpm/g)	+/-
MK8B	0-2	31.66	12.78	11.25	0.84	1.53	0.12	0.23	0.02
MK8B	4-6	31.17	11.91	10.90	0.81	1.01	0.09	0.19	0.01
MK8B	8-10	30.52	9.22	8.01	0.68	1.21	0.10	0.19	0.01
MK8B	12-14	36.06	8.79	6.89	0.65	1.90	0.15	0.27	0.02
MK8B	16-18	32.65	8.48	7.31	0.64	1.17	0.10	0.27	0.02
MK8B	20-22	33.26	6.11	4.92	0.51	1.20	0.10	0.11	0.01
MK8B	24-26	32.61	5.98	4.40	0.50	1.58	0.13	0.15	0.01
MK8B	28-30	34.41	6.17	4.72	0.50	1.45	0.12	0.14	0.01
MK8B	32-34	35.89	6.26	4.93	0.51	1.33	0.11	0.32	0.02
MK8B	36-38	35	6.56	5.56	0.53	1.00	0.09	0.32	0.02
MK8B	40-42	36.29	6.40	4.98	0.51	1.42	0.12	0.19	0.01
MK8B	44-46	35.41	5.35	3.94	0.46	1.41	0.12	0.39	0.03
MK8B	48-50	37.63	5.25	3.81	0.45	1.43	0.12	0.46	0.03
MK8B	52-54	34.18	3.76	2.33	0.36	1.43	0.12	0.25	0.02
MK8B	56-58	28.2	2.19	1.14	0.24	1.04	0.09	-0.08	-0.01
MK8B	60-62	30.07	1.35	0.32	0.17	1.04	0.09	0.06	0.00
MK8B	64-66	29.64	1.81	0.92	0.21	0.89	0.08	-0.05	-0.01
MK8B	68-70	26.8	1.25	0.49	0.16	0.76	0.07	-0.05	-0.01

Sample ID	Interval (cm)	Mass (g)	Total ²¹⁰ Pb (dpm/g)	Excess ²¹⁰ Pb (dpm/g)	+/-	²¹⁴ Bi (dpm/g)	+/-	¹³⁷ Cs (dpm/g)	+/-
MK9B	0-2	29.96	12.88	11.83	0.85	1.04	0.09	0.29	0.02
MK9B	4-6	33.25	9.85	8.98	0.70	0.88	0.08	0.33	0.02
MK9B	8-10	28.04	5.43	4.69	0.47	0.74	0.07	0.57	0.04
MK9B	12-14	28.88	5.32	4.79	0.47	0.53	0.05	3.36	0.15
MK9B	16-18	27.5	3.49	2.75	0.34	0.74	0.07	0.58	0.04
MK9B	20-22	33.08	2.41	1.43	0.26	0.99	0.09	0.18	0.01
MK9B	24-26	30.51	1.96	0.65	0.22	1.31	0.11	0.03	0.00
MK9B	28-30	32.22	1.75	0.81	0.21	0.94	0.08	-0.07	-0.01
MK9B	32-34	33.56	1.53	0.62	0.18	0.91	0.08	-0.04	0.00
MK9B	36-38	31.4	1.01	-0.12	0.14	1.13	0.10	-0.02	0.00

Sample ID	Interval (cm)	Mass (g)	Total ²¹⁰ Pb (dpm/g)	Excess ²¹⁰ Pb (dpm/g)	+/-	²¹⁴ Bi (dpm/g)	+/-	¹³⁷ Cs (dpm/g)	+/-
MK10B	0-2	35.2	12.95	11.64	0.84	1.32	0.11	0.14	0.01
MK10B	4-6	31.57	9.16	7.82	0.67	1.34	0.11	0.17	0.01
MK10B	8-10	37.75	7.26	6.15	0.56	1.11	0.09	0.29	0.02
MK10B	12-14	33.77	7.11	5.77	0.56	1.34	0.11	0.12	0.01
MK10B	16-18	32.83	6.68	5.30	0.54	1.37	0.11	0.10	0.01
MK10B	20-22	36.79	6.36	4.89	0.51	1.47	0.12	0.29	0.02
MK10B	24-26	34	6.22	4.93	0.51	1.29	0.11	0.17	0.01
MK10B	28-30	34.7	5.83	4.47	0.49	1.36	0.11	0.30	0.02
MK10B	32-34	34.73	5.25	4.04	0.45	1.20	0.10	0.22	0.02
MK10B	36-38	32.39	5.34	4.13	0.46	1.21	0.10	0.41	0.03
MK10B	40-42	37.29	5.10	3.95	0.44	1.16	0.10	0.58	0.04
MK10B	44-46	32.79	4.58	3.31	0.41	1.27	0.11	0.69	0.04
MK10B	48-50	35.48	3.60	2.48	0.34	1.12	0.09	0.48	0.03
MK10B	52-54	39.49	3.55	2.39	0.33	1.17	0.10	0.53	0.03
MK10B	56-58	35.04	2.16	0.80	0.24	1.36	0.11	0.43	0.03
MK10B	60-62	40.77	1.87	0.30	0.21	1.58	0.12	-0.01	0.00
MK10B	64-66	36.4	2.04	0.78	0.23	1.26	0.10	0.03	0.00

APPENDIX B

Appendix B contains sediment bulk data used to make plots of dry bulk density and loss-on-ignition (Figures 4-13), and also volumetric composition figures (Figures 15-24). Porosity is equal to the volume occupied by water and entrapped gas (non-solids, void space), "DBD" is dry bulk density, and "LOI" is loss-on-ignition.

Sample ID	Interval (cm)	DBD (g/cm ³)	LOI (%)	Solid volume %	Mineral volume %	Organic volume %	Porosity
MK-1B	0-2	0.307	26.77	13.58	9.95	3.64	86.42
MK-1B	2-4	0.323	26.42	14.23	10.47	3.76	85.77
MK-1B	4-6	0.329	27.34	14.60	10.61	3.99	85.40
MK-1B	6-8	0.308	28.77	13.79	9.82	3.97	86.21
MK-1B	8-10	0.346	24.63	15.11	11.39	3.72	84.89
MK-1B	10-12	0.391	21.91	16.78	13.11	3.68	83.22
MK-1B	12-14	0.382	20.95	16.28	12.87	3.41	83.72
MK-1B	14-16	0.390	23.07	16.82	12.94	3.88	83.18
MK-1B	16-18	0.322	23.94	13.97	10.63	3.35	86.03
MK-1B	18-20	0.285	25.73	12.52	9.30	3.22	87.48
MK-1B	20-22	0.249	27.62	11.07	8.01	3.06	88.93
MK-1B	22-24	0.242	28.60	10.84	7.74	3.10	89.16
MK-1B	24-26	0.194	33.94	8.99	5.94	3.05	91.01
MK-1B	26-28	0.207	31.06	9.42	6.50	2.93	90.58
MK-1B	28-30	0.214	29.53	9.63	6.78	2.84	90.37
MK-1B	30-32	0.261	26.39	11.52	8.48	3.04	88.48
MK-1B	32-34	0.266	26.84	11.77	8.61	3.16	88.23
MK-1B	34-36	0.294	25.84	12.93	9.59	3.34	87.07
MK-1B	36-38	0.291	26.35	12.85	9.47	3.39	87.15
MK-1B	38-40	0.247	31.26	11.26	7.74	3.52	88.74
MK-1B	40-42	0.274	28.35	12.26	8.78	3.47	87.74
MK-1B	42-44	0.253	29.63	11.40	8.02	3.38	88.60
MK-1B	44-46	0.184	39.16	8.82	5.37	3.46	91.18
MK-1B	46-48	0.154	49.74	8.00	4.02	3.98	92.00
MK-1B	48-50	0.148	56.29	8.07	3.53	4.54	91.93
MK-1B	50-52	0.142	58.79	7.88	3.25	4.63	92.12
MK-1B	52-54	0.147	59.74	8.22	3.31	4.91	91.78
MK-1B	54-56	0.157	58.68	8.72	3.60	5.12	91.28
MK-1B	56-58	0.150	70.49	9.19	2.71	6.48	90.81
MK-1B	58-60	0.155	60.76	8.74	3.43	5.31	91.26
MK-1B	60-62	0.156	60.61	8.79	3.46	5.33	91.21

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Sample ID	Interval (cm)	DBD (g/cm ³)	LOI (%)	Solid volume %	Mineral volume %	Organic volume %	Porosity
MK-1B	62-64	0.173	55.94	9.39	4.14	5.25	90.61
MK-1B	64-66	0.167	56.47	9.10	3.96	5.14	90.90
MK-1B	66-68	0.181	55.09	9.80	4.40	5.40	90.20
MK-1B	68-70	0.181	54.55	9.74	4.43	5.32	90.26
MK-1B	70-72	0.210	53.78	11.24	5.20	6.05	88.76
MK-1B	72-74	0.181	52.95	9.59	4.51	5.08	90.41
MK-1B	74-76	0.192	50.97	10.02	4.91	5.11	89.98
MK-1B	76-78	0.189	49.79	9.82	4.93	4.89	90.18
MK-1B	78-80	0.193	51.57	10.13	4.91	5.23	89.87
MK-1B	80-82	0.186	49.69	9.65	4.86	4.79	90.35

Sample ID	Interval (cm)	DBD (g/cm ³)	LOI (%)	Solid volume %	Mineral volume %	Organic volume %	Porosity
MK-2B	0-2	0.176	51.27	9.21	4.49	4.72	90.79
MK-2B	2-4	0.161	59.28	8.97	3.65	5.32	91.03
MK-2B	4-6	0.154	61.93	8.82	3.36	5.46	91.18
MK-2B	6-8	0.159	55.17	8.60	3.85	4.74	91.40
MK-2B	8-10	0.160	49.72	8.27	4.16	4.11	91.73
MK-2B	10-12	0.192	41.88	9.40	5.46	3.94	90.60
MK-2B	12-14	0.150	54.64	8.08	3.66	4.41	91.92
MK-2B	14-16	0.125	56.73	6.84	2.96	3.88	93.16
MK-2B	16-18	0.117	52.32	6.17	2.94	3.23	93.83
MK-2B	18-20	0.112	53.23	5.98	2.79	3.18	94.02
MK-2B	20-22	0.114	46.88	5.77	3.06	2.70	94.23
MK-2B	22-24	0.159	34.75	7.41	4.84	2.58	92.59
MK-2B	24-26	0.176	31.94	8.04	5.48	2.57	91.96
MK-2B	26-28	0.216	28.97	9.71	6.90	2.81	90.29
MK-2B	28-30	0.233	30.77	10.56	7.31	3.25	89.44
MK-2B	30-32	0.254	28.99	11.39	8.09	3.30	88.61
MK-2B	32-34	0.260	27.65	11.58	8.38	3.20	88.42
MK-2B	34-36	0.267	25.70	11.73	8.71	3.01	88.27
MK-2B	36-38	0.251	29.09	11.27	7.99	3.28	88.73
MK-2B	38-40	0.253	29.13	11.38	8.06	3.32	88.62
MK-2B	40-42	0.254	30.45	11.52	8.01	3.51	88.48
MK-2B	42-44	0.248	31.97	11.36	7.73	3.63	88.64
MK-2B	44-46	0.200	45.29	10.06	5.50	4.55	89.94
MK-2B	46-48	0.176	55.64	9.56	4.24	5.32	90.44
MK-2B	48-50	0.172	59.31	9.61	3.91	5.70	90.39
MK-2B	50-52	0.164	61.58	9.35	3.59	5.76	90.65
MK-2B	52-54	0.165	61.19	9.36	3.63	5.73	90.64
MK-2B	54-56	0.157	65.84	9.26	3.16	6.10	90.74
MK-2B	56-58	0.155	68.19	9.32	2.96	6.35	90.68
MK-2B	58-60	0.152	68.23	9.18	2.92	6.26	90.82
MK-2B	60-62	0.150	71.26	9.26	2.66	6.60	90.74
MK-2B	62-64	0.147	71.09	9.05	2.62	6.44	90.95
MK-2B	64-66	0.149	70.64	9.17	2.69	6.48	90.83
MK-2B	66-68	0.140	70.65	8.60	2.52	6.08	91.40
MK-2B	68-70	0.142	69.38	8.65	2.65	6.00	91.35
MK-2B	70-72	0.131	66.98	7.83	2.58	5.24	92.17
MK-2B	72-74	0.121	64.56	7.06	2.50	4.56	92.94
MK-2B	74-76	0.130	55.39	7.05	3.14	3.90	92.95
MK-2B	76-78	0.140	51.92	7.39	3.55	3.84	92.61
MK-2B	78-80	0.139	51.43	7.30	3.54	3.75	92.70
MK-2B	80-82	0.140	51.79	7.39	3.56	3.83	92.61

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Sample ID	Interval (cm)	DBD (g/cm ³)	LOI (%)	Solid volume %	Mineral volume %	Organic volume %	Porosity
MK-2B	82-84	0.148	53.59	7.88	3.66	4.22	92.12
MK-2B	84-86	0.153	53.08	8.14	3.82	4.32	91.86
MK-2B	86-88	0.156	53.72	8.34	3.86	4.48	91.66
MK-2B	88-90	0.165	51.45	8.67	4.21	4.46	91.33
MK-2B	90-92	0.164	52.16	8.68	4.15	4.53	91.32
MK-2B	92-94	0.178	49.29	9.18	4.65	4.52	90.82

Sample ID	Interval (cm)	DBD (g/cm ³)	LOI (%)	Solid volume %	Mineral volume %	Organic volume %	Porosity
MK-3B	0-2	0.296	33.95	13.73	9.07	4.66	86.27
MK-3B	2-4	0.248	46.12	12.53	6.75	5.78	87.47
MK-3B	4-6	0.310	40.31	15.02	8.96	6.05	84.98
MK-3B	6-8	0.262	43.98	13.02	7.29	5.73	86.98
MK-3B	8-10	0.197	52.05	10.38	4.98	5.40	89.62
MK-3B	10-12	0.212	48.26	10.85	5.62	5.24	89.15
MK-3B	12-14	0.233	38.32	11.14	6.87	4.27	88.86
MK-3B	14-16	0.199	35.15	9.32	6.04	3.27	90.68
MK-3B	16-18	0.188	33.53	8.69	5.78	2.91	91.31
MK-3B	18-20	0.193	35.28	9.04	5.85	3.19	90.96
MK-3B	20-22	0.182	37.94	8.69	5.39	3.30	91.31
MK-3B	22-24	0.166	37.53	7.86	4.91	2.95	92.14
MK-3B	24-26	0.156	36.33	7.34	4.68	2.67	92.66
MK-3B	26-28	0.167	34.42	7.75	5.08	2.67	92.25
MK-3B	28-30	0.216	32.15	9.88	6.71	3.18	90.12
MK-3B	30-32	0.243	27.30	10.77	7.83	2.94	89.23
MK-3B	32-34	0.217	32.03	9.92	6.74	3.18	90.08
MK-3B	34-36	0.240	29.54	10.80	7.61	3.19	89.20
MK-3B	36-38	0.213	26.37	9.40	6.92	2.48	90.60
MK-3B	38-40	0.193	34.26	8.96	5.89	3.07	91.04
MK-3B	40-42	0.166	33.90	7.68	5.07	2.60	92.32
MK-3B	42-44	0.177	38.13	8.46	5.23	3.22	91.54
MK-3B	44-46	0.264	29.09	11.86	8.41	3.45	88.14
MK-3B	46-48	0.260	37.04	12.31	7.75	4.56	87.69
MK-3B	48-50	0.258	27.17	11.41	8.31	3.10	88.59
MK-3B	50-52	0.221	30.35	10.00	6.96	3.03	90.00
MK-3B	52-54	0.193	29.17	8.66	6.13	2.53	91.34
MK-3B	54-56	0.220	28.42	9.82	7.03	2.79	90.18
MK-3B	56-58	0.306	24.59	13.34	10.06	3.28	86.66
MK-3B	58-60	0.390	25.02	17.06	12.79	4.27	82.94
MK-3B	60-62	0.388	24.97	16.95	12.72	4.23	83.05
MK-3B	62-64	0.335	30.71	15.17	10.51	4.66	84.83
MK-3B	64-66	0.282	35.61	13.23	8.52	4.71	86.77
MK-3B	66-68	0.283	40.73	13.73	8.14	5.59	86.27
MK-3B	68-70	0.287	37.86	13.64	8.48	5.16	86.36
MK-3B	70-72	0.302	37.50	14.33	8.95	5.37	85.67
MK-3B	72-74	0.288	36.09	13.55	8.66	4.89	86.45
MK-3B	74-76	0.271	39.26	13.00	7.90	5.10	87.00
MK-3B	76-78	0.266	38.10	12.66	7.84	4.82	87.34
MK-3B	78-80	0.250	37.79	11.88	7.39	4.49	88.12
MK-3B	80-82	0.260	35.46	12.15	7.84	4.31	87.85

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Sample ID	Interval (cm)	DBD (g/cm ³)	LOI (%)	Solid volume %	Mineral volume %	Organic volume %	Porosity
MK-3B	82-84	0.282	30.75	12.78	8.85	3.93	87.22
MK-3B	84-86	0.393	21.23	16.79	13.22	3.56	83.21
MK-3B	86-88	0.408	17.68	17.05	14.03	3.01	82.95
MK-3B	88-90	0.452	16.63	18.76	15.64	3.12	81.24
MK-3B	90-92	0.517	13.06	21.00	18.26	2.74	79.00
MK-3B	92-94	0.579	12.02	23.38	20.57	2.81	76.62
MK-3B	94-96	0.566	12.03	22.88	20.13	2.75	77.12
MK-3B	96-98	0.625	11.13	25.13	22.34	2.80	74.87

Sample ID	Interval (cm)	DBD (g/cm ³)	LOI (%)	Solid volume %	Mineral volume %	Organic volume %	Porosity
MK-4B	0-2	0.549	26.97	24.31	17.76	6.56	75.69
MK-4B	2-4	0.524	17.01	21.81	18.10	3.71	78.19
MK-4B	4-6	0.446	37.81	21.22	13.20	8.02	78.78
MK-4B	6-8	0.467	22.37	20.10	15.60	4.50	79.90
MK-4B	8-10	0.423	28.45	18.92	13.54	5.38	81.08
MK-4B	10-12	0.457	20.25	19.39	15.47	3.93	80.61
MK-4B	12-14	0.374	25.48	16.41	12.23	4.18	83.59
MK-4B	14-16	0.340	29.01	15.25	10.82	4.42	84.75
MK-4B	16-18	0.340	26.74	15.02	11.01	4.02	84.98
MK-4B	18-20	0.358	24.71	15.64	11.78	3.86	84.36
MK-4B	20-22	0.426	18.44	17.89	14.59	3.30	82.11
MK-4B	22-24	0.373	20.03	15.81	12.65	3.17	84.19
MK-4B	24-26	0.402	17.09	16.72	13.86	2.86	83.28
MK-4B	26-28	0.433	15.01	17.80	15.13	2.67	82.20
MK-4B	28-30	0.445	14.22	18.19	15.60	2.59	81.81
MK-4B	30-32	0.448	13.73	18.30	15.79	2.51	81.70
MK-4B	32-34	0.529	12.16	21.39	18.79	2.60	78.61
MK-4B	34-36	0.558	11.70	22.49	19.86	2.63	77.51
MK-4B	36-38	0.598	12.08	24.17	21.25	2.92	75.83
MK-4B	38-40	0.619	11.78	24.97	22.03	2.94	75.03
MK-4B	40-42	0.635	11.68	25.61	22.62	2.99	74.39
MK-4B	42-44	0.678	12.07	27.40	24.09	3.31	72.60
MK-4B	44-46	0.628	11.54	25.30	22.38	2.92	74.70
MK-4B	46-48	0.670	11.64	27.02	23.88	3.15	72.98
MK-4B	48-50	0.717	9.69	28.58	25.81	2.77	71.42
MK-4B	50-52	0.751	9.61	29.90	27.03	2.87	70.10
MK-4B	52-54	0.672	10.54	26.92	24.08	2.84	73.08
MK-4B	54-56	0.582	12.82	23.61	20.58	3.03	76.39
MK-4B	56-58	0.546	12.37	22.09	19.36	2.73	77.91
MK-4B	58-60	0.518	13.88	21.15	18.21	2.94	78.85
MK-4B	60-62	0.510	11.65	20.57	18.17	2.40	79.43
MK-4B	62-64	0.506	13.38	20.61	17.85	2.76	79.39
MK-4B	64-66	0.452	13.07	18.38	15.98	2.40	81.62
MK-4B	66-68	0.496	13.03	20.13	17.51	2.62	79.87
MK-4B	68-70	0.484	11.96	19.55	17.21	2.34	80.45
MK-4B	70-72	0.486	13.00	19.74	17.17	2.57	80.26
MK-4B	72-74	0.502	11.49	20.20	17.88	2.32	79.80
MK-4B	74-76	0.539	12.98	21.89	19.05	2.84	78.11
MK-4B	76-78	0.558	11.69	22.48	19.85	2.63	77.52
MK-4B	78-80	0.546	13.93	22.28	19.18	3.10	77.72
MK-4B	80-82	0.494	13.96	20.19	17.37	2.82	79.81

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Sample ID	Interval (cm)	DBD (g/cm ³)	LOI (%)	Solid volume %	Mineral volume %	Organic volume %	Porosity
MK-4B	82-84	0.572	14.03	23.39	20.11	3.28	76.61
MK-4B	84-86	0.531	13.58	21.64	18.70	2.94	78.36
MK-4B	86-88	0.484	18.54	20.31	16.55	3.76	79.69
MK-4B	88-90	0.435	19.22	18.35	14.83	3.53	81.65
MK-4B	90-92	0.458	19.07	19.30	15.62	3.68	80.70
MK-4B	92-94	0.492	15.18	20.24	17.17	3.07	79.76
MK-4B	94-96	0.486	17.64	20.29	16.71	3.58	79.71

Sample ID	Interval (cm)	DBD (g/cm ³)	LOI (%)	Solid volume %	Mineral volume %	Organic volume %	Porosity
MK-5B	0-2	0.455	21.98	19.53	15.24	4.29	80.47
MK-5B	4-6	0.447	22.97	19.29	14.86	4.43	80.71
MK-5B	8-10	0.379	26.64	16.76	12.29	4.46	83.24
MK-5B	12-14	0.338	37.60	16.06	10.02	6.04	83.94
MK-5B	16-18	0.342	34.82	15.95	10.39	5.55	84.05
MK-5B	20-22	0.344	29.16	15.46	10.95	4.51	84.54
MK-5B	24-26	0.354	19.45	14.95	12.04	2.91	85.05
MK-5B	28-30	0.359	18.20	15.03	12.30	2.74	84.97
MK-5B	32-34	0.396	14.91	16.25	13.83	2.42	83.75
MK-5B	36-38	0.390	15.85	16.09	13.54	2.55	83.91
MK-5B	40-42	0.368	17.62	15.35	12.65	2.71	84.65
MK-5B	44-46	0.365	19.34	15.41	12.43	2.98	84.59
MK-5B	48-50	0.371	19.48	15.65	12.60	3.05	84.35
MK-5B	52-54	0.403	20.65	17.13	13.59	3.54	82.87
MK-5B	56-58	0.500	16.57	20.73	17.30	3.43	79.27
MK-5B	60-62	0.464	14.82	19.05	16.22	2.82	80.95
MK-5B	64-66	0.499	15.78	20.60	17.35	3.25	79.40

Sample ID	Interval (cm)	DBD (g/cm ³)	LOI (%)	Solid volume %	Mineral volume %	Organic volume %	Porosity
MK-6B	0-2	0.538	12.76	21.82	19.04	2.78	78.18
MK-6B	4-6	0.501	13.72	20.46	17.65	2.81	79.54
MK-6B	8-10	0.471	10.14	18.81	16.90	1.91	81.19
MK-6B	12-14	0.467	17.09	19.43	16.11	3.32	80.57
MK-6B	16-18	0.522	15.46	21.52	18.19	3.33	78.48
MK-6B	20-22	0.486	14.47	19.91	17.03	2.88	80.09
MK-6B	24-26	0.505	11.79	20.36	17.96	2.40	79.64
MK-6B	28-30	0.535	10.91	21.47	19.13	2.34	78.53
MK-6B	32-34	0.514	12.45	20.83	18.24	2.59	79.17
MK-6B	36-38	0.495	15.47	20.42	17.26	3.16	79.58
MK-6B	40-42	0.483	14.17	19.75	16.95	2.80	80.25
MK-6B	44-46	0.474	15.48	19.55	16.52	3.03	80.45
MK-6B	48-50	0.469	12.97	19.04	16.57	2.47	80.96
MK-6B	52-54	0.451	13.14	18.34	15.93	2.41	81.66
MK-6B	56-58	0.471	11.19	18.95	16.83	2.12	81.05
MK-6B	60-62	0.430	12.90	17.45	15.20	2.25	82.55
MK-6B	64-66	0.401	12.93	16.30	14.19	2.11	83.70
MK-6B	68-70	0.400	15.20	16.45	13.95	2.50	83.55
MK-6B	72-74	0.368	16.71	15.27	12.72	2.55	84.73
MK-6B	76-78	0.389	14.51	15.93	13.62	2.31	84.07

Sample ID	Interval (cm)	DBD (g/cm ³)	LOI (%)	Solid volume %	Mineral volume %	Organic volume %	Porosity
MK-7B	0-2	0.511	16.54	21.18	17.68	3.50	78.82
MK-7B	4-6	0.525	18.57	22.07	17.97	4.10	77.93
MK-7B	8-10	0.538	16.92	22.39	18.60	3.79	77.61
MK-7B	12-14	0.428	18.76	17.98	14.61	3.37	82.02
MK-7B	16-18	0.371	21.19	15.85	12.49	3.36	84.15
MK-7B	20-22	0.418	22.84	18.02	13.90	4.12	81.98
MK-7B	24-26	0.401	21.59	17.16	13.45	3.70	82.84
MK-7B	28-30	0.271	35.35	12.66	8.19	4.48	87.34
MK-7B	32-34	0.250	28.34	11.18	8.01	3.17	88.82
MK-7B	36-38	0.221	31.11	10.06	6.93	3.13	89.94
MK-7B	40-42	0.204	30.65	9.23	6.40	2.83	90.77
MK-7B	44-46	0.202	30.22	9.12	6.37	2.76	90.88
MK-7B	48-50	0.221	26.95	9.80	7.16	2.64	90.20
MK-7B	52-54	0.193	28.80	8.62	6.14	2.48	91.38
MK-7B	56-58	0.164	38.51	7.83	4.81	3.02	92.17
MK-7B	60-62	0.174	32.48	7.98	5.39	2.59	92.02
MK-7B	64-66	0.196	32.44	9.00	6.08	2.92	91.00
MK-7B	68-70	0.218	27.21	9.67	7.04	2.63	90.33
MK-7B	72-74	0.247	25.92	10.85	8.04	2.81	89.15
MK-7B	76-78	0.210	32.25	9.61	6.51	3.10	90.39
MK-7B	80-82	0.258	26.93	11.41	8.34	3.07	88.59
MK-7B	84-86	0.217	28.34	9.69	6.95	2.75	90.31
MK-7B	88-90	0.266	21.89	11.42	8.92	2.50	88.58
MK-7B	92-94	0.200	31.53	9.13	6.25	2.88	90.87
MK-7B	96-98	0.214	33.02	9.84	6.59	3.25	90.16

Sample ID	Interval (cm)	DBD (g/cm ³)	LOI (%)	Solid volume %	Mineral volume %	Organic volume %	Porosity
MK-8B	0-2	0.377	16.28	15.63	13.09	2.54	84.37
MK-8B	4-6	0.364	15.23	14.98	12.70	2.28	85.02
MK-8B	8-10	0.353	16.60	14.66	12.23	2.43	85.34
MK-8B	12-14	0.390	15.65	16.12	13.59	2.52	83.88
MK-8B	16-18	0.433	13.77	17.66	15.23	2.43	82.34
MK-8B	20-22	0.405	16.30	16.77	14.04	2.73	83.23
MK-8B	24-26	0.429	15.33	17.66	14.96	2.71	82.34
MK-8B	28-30	0.458	13.86	18.72	16.12	2.59	81.28
MK-8B	32-34	0.443	14.43	18.16	15.54	2.62	81.84
MK-8B	36-38	0.438	14.69	17.98	15.34	2.64	82.02
MK-8B	40-42	0.454	14.24	18.57	15.92	2.64	81.43
MK-8B	44-46	0.428	15.61	17.66	14.90	2.76	82.34
MK-8B	48-50	0.474	14.88	19.46	16.57	2.90	80.54
MK-8B	52-54	0.369	17.49	15.41	12.71	2.70	84.59
MK-8B	56-58	0.256	26.40	11.31	8.32	2.99	88.69
MK-8B	60-62	0.276	25.65	12.12	9.01	3.11	87.88
MK-8B	64-66	0.258	25.98	11.33	8.39	2.94	88.67
MK-8B	68-70	0.235	29.50	10.57	7.45	3.12	89.43
MK-8B	72-74	0.248	26.17	10.91	8.05	2.85	89.09
MK-8B	76-78	0.226	29.35	10.17	7.19	2.99	89.83
MK-8B	80-82	0.297	24.79	12.97	9.75	3.21	87.03
MK-8B	84-86	0.393	19.62	16.62	13.36	3.26	83.38
MK-8B	88-90	0.342	24.09	14 84	11 27	3.58	85 16

Sample ID	Interval (cm)	DBD (g/cm ³)	LOI (%)	Solid volume %	Mineral volume %	Organic volume %	Porosity
MK-9B	0-2	0.438	21.86	18.76	14.66	4.10	81.24
MK-9B	4-6	0.430	24.52	18.73	14.14	4.59	81.27
MK-9B	8-10	0.322	33.35	14.86	9.91	4.96	85.14
MK-9B	12-14	0.369	27.86	16.45	11.87	4.58	83.55
MK-9B	16-18	0.281	33.23	12.96	8.65	4.31	87.04
MK-9B	20-22	0.312	28.27	13.91	9.98	3.93	86.09
MK-9B	24-26	0.410	19.98	17.37	13.90	3.47	82.63
MK-9B	28-30	0.411	23.53	17.79	13.61	4.19	82.21
MK-9B	32-34	0.406	23.98	17.61	13.39	4.22	82.39
MK-9B	36-38	0.403	21.86	17.27	13.49	3.78	82.73
MK-9B	40-42	0.384	23.46	16.63	12.73	3.90	83.37
MK-9B	44-46	0.491	14.60	20.14	17.20	2.94	79.86
MK-9B	48-50	0.518	13.60	21.11	18.24	2.87	78.89
MK-9B	52-54	0.433	17.03	18.03	14.96	3.07	81.97
MK-9B	56-58	0.399	18.75	16.79	13.64	3.15	83.21
MK-9B	60-62	0.374	20.23	15.88	12.67	3.21	84.12
MK-9B	64-66	0.374	18.30	15.68	12.81	2.87	84.32
MK-9B	68-70	0.415	17.42	17.31	14.30	3.02	82.69
MK-9B	72-74	0.451	14.75	18.51	15.78	2.73	81.49
MK-9B	76-78	0.486	13.25	19.77	17.15	2.62	80.23

Sample ID	Interval (cm)	DBD (g/cm ³)	LOI (%)	Solid volume %	Mineral volume %	Organic volume %	Porosity
MK-10B	0-2	0.475	16.69	19.74	16.44	3.29	80.26
MK-10B	4-6	0.514	12.62	20.83	18.20	2.63	79.17
MK-10B	8-10	0.478	14.52	19.57	16.73	2.84	80.43
MK-10B	12-14	0.495	14.73	20.32	17.33	2.99	79.68
MK-10B	16-18	0.479	13.93	19.55	16.82	2.72	80.45
MK-10B	20-22	0.477	13.61	19.43	16.79	2.64	80.57
MK-10B	24-26	0.478	13.02	19.42	16.89	2.53	80.58
MK-10B	28-30	0.494	14.06	20.19	17.35	2.84	79.81
MK-10B	32-34	0.459	14.31	18.79	16.10	2.69	81.21
MK-10B	36-38	0.469	14.55	19.22	16.43	2.80	80.78
MK-10B	40-42	0.490	14.25	20.05	17.19	2.86	79.95
MK-10B	44-46	0.502	14.96	20.62	17.53	3.08	79.38
MK-10B	48-50	0.465	18.62	19.55	15.91	3.64	80.45
MK-10B	52-54	0.506	14.92	20.81	17.70	3.10	79.19
MK-10B	56-58	0.511	13.64	20.85	18.00	2.84	79.15
MK-10B	60-62	0.552	11.51	22.22	19.66	2.56	77.78
MK-10B	64-66	0.416	16.57	17.26	14.40	2.86	82.74
MK-10B	68-70	0.441	16.46	18.28	15.27	3.01	81.72
MK-10B	72-74	0.393	17.00	16.36	13.58	2.78	83.64
MK-10B	76-78	0.422	16.02	17.45	14.65	2.80	82.55
MK-10B	80-82	0.359	21.30	15.34	12.08	3.27	84.66
MK-10B	84-86	0.415	20.57	17.63	14.00	3.63	82.37

APPENDIX C

Appendix C contains grain-size measurements used to produce grain-size distributions in Figures 15 through 24, ternary diagrams (Figures 25 & 26) and plots of LOI vs. grain size (Figure 28).

Sample	Interval	Sand	Silt	Clay	Sortable silt	Fine silt	Clay
ID	(cm)	(> 63 µm)	(2-63 µm)	(<2 µm)	(10-63 µm)	(2-10 µm)	(<2 µm)
ID	(em)	(wt %)	(wt %)	(wt %)	(wt %)	(wt %)	(wt %)
MK1B	0-2	27.956	65.162	6.882	25.637	59.908	14.456
MK1B	4-6	22.153	73.588	4.259	26.972	63.569	9.459
MK1B	8-10	18.174	77.244	4.583	28.031	62.857	9.112
MK1B	12-14	21.336	73.820	4.844	24.089	65.794	10.117
MK1B	16-18	20.836	74.442	4.721	25.844	64.760	9.396
MK1B	20-22	24.848	71.809	3.343	33.451	59.405	7.144
MK1B	24-26	24.735	71.697	3.568	30.704	61.224	8.072
MK1B	28-30	52.257	45.915	1.828	36.981	56.562	6.457
MK1B	32-34	31.372	65.886	2.742	38.079	55.431	6.491
MK1B	36-38	32.562	64.786	2.652	31.882	61.891	6.226
MK1B	40-42	31.346	65.978	2.676	31.966	61.621	6.413
MK1B	44-46	47.383	50.912	1.705	48.502	46.141	5.357
MK1B	48-50	50.554	48.250	1.196	51.421	44.444	4.135
MK1B	52-54	62.355	36.960	0.685	62.531	34.027	3.442
MK1B	56-58	53.711	45.454	0.835	58.037	38.816	3.147
MK1B	60-62	53.154	46.047	0.799	62.451	34.626	2.922
MK1B	64-66	32.331	66.412	1.257	58.266	38.559	3.175
MK1B	68-70	47.018	51.887	1.094	55.204	41.229	3.567
MK1B	72-74	40.974	57.967	1.059	53.580	43.303	3.117
MK1B	76-78	40.890	58.155	0.956	58.325	38.928	2.747
MK1B	80-82	32.930	65.228	1.842	44.848	50.647	4.505

Sample	Interval	Sand	Silt	Clay	Sortable silt	Fine silt	Clay
ID	(cm)	$(> 63 \mu m)$ (wt %)	$(2-63 \ \mu m)$	(<2µm) (wt %)	$(10-63\mu m)$	$(2-10\mu m)$	$(<2\mu m)$ (wt %)
MK2B	0-2	41.760	56.490	1.750	49.485	45.456	5.059
MK2B	4-6	42.101	56.785	1.113	64.733	32.026	3.242
MK2B	8-10	48.403	50.258	1.339	51.919	43.665	4.416
MK2B	12-14	51.647	47.754	0.599	72.347	25.454	2.199
MK2B	16-18	42.830	55.695	1.475	50.670	44.794	4.536
MK2B	20-22	40.523	58.078	1.398	51.878	44.271	3.851
MK2B	24-26	44.891	53.241	1.867	40.739	53.844	5.417
MK2B	28-30	38.465	59.928	1.606	45.734	50.061	4.205
MK2B	32-34	31.306	67.274	1.421	51.239	45.462	3.300
MK2B	36-38	35.538	61.568	2.893	29.929	62.466	7.605
MK2B	40-42	25.783	71.295	2.922	38.233	55.415	6.352
MK2B	44-46	48.319	50.984	0.697	68.635	29.098	2.267
MK2B	48-50	58.434	40.774	0.792	62.677	34.080	3.244
MK2B	52-54	61.779	37.374	0.846	59.563	36.587	3.851
MK2B	56-58	58.105	40.690	1.205	53.844	41.511	4.645
MK2B	60-62	62.874	36.437	0.689	61.278	35.486	3.236
MK2B	64-66	50.983	48.060	0.957	57.159	39.181	3.660
MK2B	68-70	62.263	36.978	0.759	62.942	33.532	3.526
MK2B	72-74	54.892	44.177	0.931	60.524	35.720	3.756
MK2B	76-78	52.051	46.796	1.153	55.377	40.568	4.054
MK2B	80-82	42.222	56.017	1.761	50.669	44.443	4.889
MK2B	84-86	57.287	41.670	1.043	52.124	43.870	4.006
MK2B	88-90	39.760	58.687	1.553	56.191	39.210	4.598
MK2B	92-94	38.861	58.823	2.316	39.954	53.983	6.063

Sample	Interval	Sand	Silt	Clay	Sortable silt	Fine silt	Clay
ID	(cm)	$(> 63 \mu m)$	$(2-63 \ \mu m)$	(<2µm)	$(10-63\mu m)$	$(2-10\mu m)$	(<2µm)
	× /	(wt %)	(wt %)	(wt %)	(wt %)	(wt %)	(wt %)
MK3B	0-2	29.240	68.065	2.694	38.800	54.976	6.225
MK3B	4-6	36.417	61.959	1.624	43.876	51.952	4.172
MK3B	8-10	88.328	11.428	0.243	52.600	43.908	3.492
MK3B	12-14	41.806	56.531	1.663	44.414	50.936	4.651
MK3B	16-18	28.154	69.029	2.817	36.697	57.021	6.282
MK3B	20-22	35.958	61.787	2.255	39.028	55.231	5.741
MK3B	24-26	34.857	61.995	3.148	35.468	56.570	7.962
MK3B	28-30	22.501	72.743	4.756	29.765	61.236	9.000
MK3B	32-34	28.267	65.950	5.782	21.885	67.108	11.007
MK3B	36-38	26.784	68.080	5.137	24.362	65.646	9.992
MK3B	40-42	46.383	50.124	3.494	26.301	64.011	9.688
MK3B	44-46	25.470	68.116	6.414	20.613	67.638	11.749
MK3B	48-50	31.728	61.930	6.341	17.127	70.162	12.711
MK3B	52-54	25.693	68.531	5.775	24.656	64.692	10.652
MK3B	56-58	22.753	70.962	6.285	23.908	64.875	11.217
MK3B	60-62	26.302	68.095	5.603	26.191	63.417	10.393
MK3B	64-66	45.475	50.630	3.895	24.639	65.095	10.266
MK3B	68-70	47.937	49.273	2.790	39.708	52.574	7.718
MK3B	72-74	34.553	61.479	3.968	34.020	57.620	8.360
MK3B	76-78	29.387	66.816	3.797	36.522	55.592	7.886
MK3B	80-82	16.506	78.328	5.166	30.123	61.172	8.705
MK3B	84-86	28.603	66.244	5.154	21.346	68.663	9.991
MK3B	88-90	13.255	80.586	6.160	23.028	67.195	9.776
MK3B	92-94	7.103	86.868	6.029	21.749	68.727	9.524
MK3B	96-98	2.583	90.664	6.753	21.862	68.013	10.125

Sample	Interval	Sand	Silt	Clay	Sortable silt	Fine silt	Clay
ID	(cm)	(> 63µm)	(2-63 µm)	(<2µm)	(10-63µm)	(2-10µm)	(<2µm)
ID	(CIII)	(wt %)	(wt %)	(wt %)	(wt %)	(wt %)	(wt %)
MK4B	0-2	12.572	81.705	5.723	25.537	64.853	9.610
MK4B	4-6	12.895	80.183	6.923	18.911	69.678	11.411
MK4B	8-10	16.121	77.503	6.377	24.552	62.759	12.689
MK4B	12-14	36.343	59.337	4.320	22.949	66.551	10.500
MK4B	16-18	13.267	80.700	6.033	26.125	63.347	10.528
MK4B	20-22	10.374	82.832	6.794	15.689	72.549	11.762
MK4B	24-26	7.019	85.995	6.986	24.011	64.765	11.224
MK4B	28-30	10.495	82.487	7.018	16.927	71.004	12.069
MK4B	32-34	14.307	80.036	5.657	27.682	62.441	9.878
MK4B	36-38	12.069	80.245	7.686	19.989	67.394	12.617
MK4B	40-42	12.008	81.288	6.704	22.597	65.879	11.524
MK4B	44-46	2.326	90.739	6.936	22.741	66.449	10.811
MK4B	48-50	2.491	90.425	7.084	21.638	67.449	10.914
MK4B	52-54	10.000	83.418	6.582	24.805	63.562	11.633
MK4B	56-58	17.298	75.679	7.023	13.952	73.122	12.926
MK4B	60-62	4.361	89.704	5.935	26.248	63.987	9.765
MK4B	64-66	8.826	84.904	6.270	26.615	62.910	10.474
MK4B	68-70	8.656	84.554	6.790	24.349	64.155	11.496
MK4B	72-74	7.387	86.003	6.610	22.489	65.936	11.574
MK4B	76-78	10.884	81.804	7.312	19.681	66.465	13.854
MK4B	80-82	9.424	85.476	5.100	32.381	57.906	9.713
MK4B	84-86	10.234	84.688	5.079	28.494	61.893	9.613
MK4B	88-90	16.169	78.638	5.193	26.794	62.688	10.518
MK4B	92-94	12.535	82.192	5.273	28.085	61.546	10.370

Sample ID	Interval (cm)	Sand (> 63µm) (wt %)	Silt (2-63 µm) (wt %)	Clay (<2µm) (wt %)	Sortable silt (10-63µm) (wt %)	Fine silt (2-10µm) (wt %)	Clay (<2µm) (wt %)
MK5B	0-2	6.848	85.391	7.761	20.819	65.514	13.667
MK5B	4-6	8.892	82.050	9.057	14.680	69.235	16.085
MK5B	8-10	11.860	80.919	7.221	22.535	63.585	13.880
MK5B	12-14	22.244	72.337	5.419	26.747	61.344	11.909
MK5B	16-18	30.763	64.711	4.526	25.909	61.340	12.751
MK5B	20-22	30.916	64.940	4.144	27.416	62.632	9.952
MK5B	24-26	12.964	80.940	6.096	25.618	62.739	11.643
MK5B	28-30	9.504	83.572	6.924	21.274	65.765	12.961
MK5B	32-34	12.475	81.695	5.830	26.883	61.560	11.557
MK5B	36-38	9.470	83.779	6.751	23.922	63.611	12.467
MK5B	40-42	14.677	79.248	6.075	25.348	64.239	10.413
MK5B	44-46	10.428	82.424	7.148	23.084	65.127	11.789
MK5B	48-50	8.153	85.396	6.451	26.603	63.099	10.298
MK5B	52-54	11.791	80.772	7.437	19.077	69.574	11.348
MK5B	56-58	19.778	74.619	5.604	24.873	65.170	9.957
MK5B	60-62	14.597	78.614	6.789	22.792	66.170	11.038
MK5B	64-66	6.154	87.660	6.186	23.924	66.528	9.547

Sample ID	Interval (cm)	Sand (> 63µm) (wt %)	Silt (2-63 µm) (wt %)	Clay (<2µm) (wt %)	Sortable silt (10-63µm) (wt %)	Fine silt (2-10µm) (wt %)	Clay (<2µm) (wt %)
MK6B	0-2	9.580	83 413	7 007	23 323	62 591	14 086
MK6B	4-6	7.037	85.256	7.707	23.860	62.042	14.098
MK6B	8-10	5.147	87.197	7.656	20.789	65.389	13.822
MK6B	12-14	14.142	79.902	5.955	24.491	63.639	11.870
MK6B	16-18	12.613	81.615	5.772	29.375	59.266	11.359
MK6B	20-22	7.183	85.675	7.143	15.741	71.353	12.906
MK6B	24-26	3.650	89.818	6.532	24.265	64.186	11.549
MK6B	28-30	2.863	91.493	5.644	25.680	64.773	9.548
MK6B	32-34	5.243	88.791	5.966	18.860	70.368	10.771
MK6B	36-38	9.780	83.513	6.707	18.811	69.082	12.106
MK6B	40-42	8.342	85.195	6.462	18.539	68.700	12.761
MK6B	44-46	7.258	86.764	5.978	22.965	66.566	10.468
MK6B	48-50	12.940	81.840	5.220	21.505	68.718	9.777
MK6B	52-54	4.954	88.063	6.984	17.900	70.380	11.720
MK6B	56-58	6.838	84.386	8.775	15.480	68.857	15.663
MK6B	60-62	8.179	86.086	5.734	30.425	59.108	10.467
MK6B	64-66	6.771	87.773	5.456	27.377	62.295	10.328
MK6B	68-70	11.389	83.549	5.062	32.324	58.036	9.640
MK6B	72-74	12.863	81.170	5.967	26.847	61.188	11.965
MK6B	76-78	10 258	84 183	5 560	30 680	59 012	10 308

Sample ID	Interval (cm)	Sand (> $63\mu m$)	Silt (2-63 μ m)	Clay $(<2\mu m)$	Sortable silt (10-63 μ m)	Fine silt $(2-10\mu m)$	Clay $(<2\mu m)$
MV7D	0.2	(Wl %) 12 144	(WL %) 80 425	(Wl %) 6.421	(WL %)	(WL %)	(WL %)
MK7D	0-2	13.144	80.423	0.451	22.100	60.007	12.460
	4-0	/./84	84.449	1./0/	19.383	08.137	12.400
MK/B	8-10	6.08/	85.506	8.407	17.673	69.554	12.773
MK/B	12-14	12.899	78.727	8.373	15.674	/0.0/2	14.254
MK7B	16-18	10.884	82.270	6.846	26.689	61.651	11.660
MK7B	20-22	11.699	78.780	9.520	12.523	70.837	16.639
MK7B	24-26	10.741	81.881	7.378	23.132	64.829	12.039
MK7B	28-30	20.531	73.440	6.029	24.702	64.074	11.224
MK7B	32-34	15.315	79.302	5.383	31.329	58.873	9.798
MK7B	36-38	10.220	82.693	7.087	23.702	64.684	11.614
MK7B	40-42	13.627	78.839	7.533	20.500	66.616	12.884
MK7B	44-46	8.813	85.881	5.306	31.716	59.847	8.437
MK7B	48-50	17.566	80.299	2.135	56.677	39.348	3.975
MK7B	52-54	21.454	74.896	3.650	38.642	53.771	7.586
MK7B	56-58	23.831	73.754	2.415	52.529	42.567	4.905
MK7B	60-62	17.367	78.568	4.065	39.362	53.615	7.023
MK7B	64-66	22.472	74.247	3.281	43.093	50.410	6.497
MK7B	68-70	16.867	77.614	5.519	27.929	61.703	10.368
MK7B	72-74	14.566	81.039	4.395	35.875	55.991	8.133
MK7B	76-78	11.330	84.554	4.116	38.177	54.939	6.884
MK7B	80-82	14.680	81.742	3.577	44.158	49.678	6.164
MK7B	84-86	13.521	83.307	3.172	44.047	50.463	5.490
MK7B	88-90	9.173	83.563	7.264	17.790	70.284	11.926
MK7B	92-94	16.943	78.952	4.106	31.596	60.987	7.417
MK7B	96-98	23.840	73.328	2.832	40.276	54.342	5.382

Sample	Interval	Sand	Silt	Clay	Sortable silt	Fine silt	Clay
ID	(cm)	(> 63µm)	(2-63 µm)	(<2µm)	(10-63µm)	(2-10µm)	(<2µm)
12	(UIII)	(wt %)	(wt %)	(wt %)	(wt %)	(wt %)	(wt %)
MK8B	0-2	8.717	84.126	7.157	25.096	63.655	11.249
MK8B	4-6	5.223	86.805	7.972	20.677	66.421	12.902
MK8B	8-10	7.957	84.647	7.395	22.399	65.428	12.173
MK8B	12-14	3.096	89.471	7.433	23.872	65.127	11.002
MK8B	16-18	4.635	87.934	7.431	22.949	65.205	11.847
MK8B	20-22	6.945	86.152	6.903	26.156	63.129	10.715
MK8B	24-26	7.677	85.887	6.436	28.188	61.318	10.494
MK8B	28-30	5.120	87.501	7.379	24.166	64.687	11.147
MK8B	32-34	5.762	84.964	9.274	20.014	66.265	13.721
MK8B	36-38	7.899	84.544	7.556	26.071	62.297	11.632
MK8B	40-42	7.716	83.710	8.574	22.882	64.741	12.377
MK8B	44-46	7.959	83.757	8.284	22.558	64.396	13.045
MK8B	48-50	5.368	85.468	9.165	17.172	69.417	13.411
MK8B	52-54	10.355	83.923	5.722	31.564	58.881	9.555
MK8B	56-58	18.165	76.725	5.110	34.566	55.693	9.741
MK8B	60-62	10.959	82.835	6.206	26.404	62.832	10.764
MK8B	64-66	17.824	77.772	4.404	35.475	55.902	8.623
MK8B	68-70	11.759	82.888	5.353	26.934	63.829	9.237
MK8B	72-74	11.531	83.414	5.055	31.095	60.256	8.649
MK8B	76-78	13.927	81.006	5.067	25.239	65.891	8.870
MK8B	80-82	12.144	82.732	5.124	31.808	59.609	8.583
MK8B	84-86	11.405	84.224	4.371	33.381	59.373	7.247
MK8B	88-90	14 909	80.061	5 030	27 838	62 496	9 666

Sample ID	Interval (cm)	Sand (> 63µm) (wt %)	Silt (2-63 µm) (wt %)	Clay (<2µm) (wt %)	Sortable silt (10-63µm) (wt %)	Fine silt (2-10µm) (wt %)	Clay (<2µm) (wt %)
MK9B	0-2	10.479	84.272	5.249	21.719	68.650	9.631
MK9B	4-6	16.792	78.623	4.585	24,599	66.228	9.173
MK9B	8-10	17.674	78.597	3.729	33.062	59.018	7.920
MK9B	12-14	20.703	75.681	3.616	34.917	57.048	8.036
MK9B	16-18	23.757	72.312	3.931	30.000	61.909	8.091
MK9B	20-22	17.901	77.494	4.604	26.961	63.595	9.443
MK9B	24-26	5.019	89.936	5.046	27.039	63.792	9.170
MK9B	28-30	9.485	85.523	4.992	29.450	61.586	8.964
MK9B	32-34	18.811	76.221	4.968	24.227	66.107	9.667
MK9B	36-38	22.085	74.078	3.837	26.437	65.319	8.244
MK9B	40-42	10.487	84.740	4.772	29.950	60.896	9.154
MK9B	44-46	5.478	88.862	5.661	19.246	70.710	10.044
MK9B	48-50	5.057	88.128	6.815	24.906	64.731	10.363
MK9B	52-54	15.356	81.087	3.557	44.947	48.210	6.843
MK9B	56-58	16.752	78.829	4.419	33.659	57.601	8.740
MK9B	60-62	15.672	79.890	4.438	35.989	56.271	7.739
MK9B	64-66	12.943	81.220	5.836	24.447	65.807	9.746
MK9B	68-70	7.840	86.966	5.194	30.388	61.529	8.083
MK9B	72-74	6.744	86.212	7.044	19.509	69.466	11.024
MK9B	76-78	4.692	89.284	6.023	23.838	67.125	9.037

Sample ID	Interval (cm)	Sand (> 63µm) (wt %)	Silt (2-63 µm) (wt %)	Clay (<2µm) (wt %)	Sortable silt (10-63µm) (wt %)	Fine silt (2-10µm) (wt %)	Clay (<2µm) (wt %)
MK10B	0-2	5.678	87.635	6.688	22.054	66.999	10.947
MK10B	4-6	6.023	86.974	7.003	20.881	67.713	11.405
MK10B	8-10	2.273	90.129	7.598	18.819	69.271	11.910
MK10B	12-14	3.229	87.468	9.303	11.986	73.319	14.696
MK10B	16-18	2.080	90.206	7.714	12.348	75.635	12.017
MK10B	20-22	2.057	91.191	6.753	18.290	68.204	13.506
MK10B	24-26	2.885	90.537	6.578	22.331	66.324	11.345
MK10B	28-30	4.643	87.506	7.852	14.355	73.432	12.213
MK10B	32-34	4.994	88.437	6.570	19.414	69.443	11.143
MK10B	36-38	9.270	85.458	5.273	28.677	61.463	9.860
MK10B	40-42	6.898	87.893	5.209	29.107	60.954	9.939
MK10B	44-46	11.940	82.250	5.810	20.471	68.603	10.926
MK10B	48-50	4.631	89.651	5.718	26.877	63.340	9.783
MK10B	52-54	6.258	89.222	4.520	31.805	59.200	8.995
MK10B	56-58	3.611	91.223	5.166	23.793	66.358	9.849
MK10B	60-62	3.311	91.724	4.965	28.356	62.173	9.471
MK10B	64-66	6.811	88.522	4.667	30.941	59.638	9.421
MK10B	68-70	9.825	84.216	5.960	22.221	67.056	10.723
MK10B	72-74	7.875	85.741	6.384	18.137	70.678	11.185
MK10B	76-78	7.448	87.490	5.063	28.786	61.479	9.735
MK10B	80-82	4.865	90.847	4.288	36.311	55.211	8.478
MK10B	84-86	11.939	82.398	5.663	19.112	70.603	10.285